USE OF A REPULSION MOTOR IN A POSITION SERVOMECHANISM

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Approved:

Thesis Advisor

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I wish to express my sincere appreciation to Doctor Frank O. Nottingham for his valuable criticism and guidance throughout the preparation of this thesis. I am indebted to Professor J. M. Bailey for his helpful suggestions. A special note of appreciation is due my wife, Betty, for her encouragement and understanding.

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ABSTRACT

There are many uses in industry for a closed loop system that will accurately position some output member in response to some input command signal. One such application would be positioning a valve to control the flow of liquid into a chemical reactor. Because of their ease of control, electric motors are used quite extensively as the power element. In applications where high torque levels are required, d-c motors are used, and where low torque requirements exist two phase a-c servo motors can be used.

Because alternating current is so readily available, a need exists for an a-c drive motor which can be used in a positional system requiring high torque levels.

One such device is the repulsion motor, which utilizes alternating current and is capable of developing a high starting torque. This amount of torque is usually comparable to that of a direct current series motor.

The purpose of this study was to investigate the use of a repulsion motor in an a-c positional servomechanism which will be expected to deliver a high starting torque.

The system in this study makes use of the principle that torque is developed in a repulsion motor when the brushes are short circuited. Reversing service in the motor, which is a requirement in an all-electric positioning system, is obtained by the use of two sets of brushes which were installed on each side of the mechanical neutral axis. The desired direction of rotation is obtained by the application of a short circuit

across the appropriate set of brushes. Grid controlled gas tubes (thyratrons) were used as the short circuiting devices. The tubes were connected directly across the secondary of a transformer while the primary side was connected to the brushes. When the tubes conduct, an effective short circuit occurs. When the tubes do not conduct, an effective open circuit results.

An actual system was constructed with a repulsion motor which was rated at one third horsepower. Starting torque tests, open loop frequency response tests, and a velocity test were performed on the working system. The motor of the system delivered a high starting torque which may be expected of a repulsion motor, and the system appeared to operate satisfactorily as a position servomechanism.

Two advantages of the proposed system are apparent. One, the motor has a high starting torque for an a-c position servomechanism, and, two, the principle of the controller component (which contains the gas tubes) has an inherent low time constant.

Further work can be done to devise some means to decrease the excessive electric power used by the system when it operates at low speeds or is at rest.

CHAPTER I

INTRODUCTION

There are many uses in industry for a closed loop system that will accurately position some output member in response to some input command signal. One such application would be positioning a valve to control the flow of liquid into a chemical reactor. Because of their ease of control, electric motors are used quite extensively as the power element. In applications where high torque levels are required, d-c motors are used, and where low torque requirements exist two phase a-c servo motors can be used.

Because alternating current is so readily available, a need exists for an a-c drive motor which can be used in a positional system requiring high torque levels.

One such device is the repulsion motor, which utilizes alternating current and is capable of developing a high starting torque. This amount of torque is usually comparable to that of a direct current series motor.

The ability of a motor to operate in either direction of rotation is necessary in an all-electric positioning system. In a repulsion motor, reversal of the brush displacement from the initial brush displacement causes a reversal in the direction of rotation. The motor operates satisfactorily when the brush position is about 45 electrical degrees from the mechanical neutral. For this proposed positioning system, reversing service is obtained by the use of two sets of brushes which were placed about

45 electrical degrees on both sides of the mechanical neutral of the motor. The desired direction of rotation is obtained by the application of a short circuit to the appropriate set of brushes.

The controller for a servomechanism using a repulsion motor as the motoring component would simply consist of some device to short circuit either of the two sets of brushes, while the power source is permanently supplied to the stator of the motor. Grid controlled gas tubes may be well suited for use in the controller, since gas tubes are capable of transmitting large currents.

The purpose of this study was to investigate the use of a repulsion motor in an a-c positional servomechanism which will be expected to deliver a high starting torque.

CHAPTER II

THE SYSTEM AND ITS OPERATION

Block diagram of the closed loop system.--A block diagram of the proposed closed loop system is shown in Fig. 1.

Assume an input signal is introduced into the system of Fig. 1. The signal is amplified and connected to a switching device. The switching device controls the motor in proportion to the amount of error signal received by it, and the motor delivers the output power in terms of rotation of a shaft. A signal representing the output position of the shaft is fed back to the error detector which produces the error voltage. This error voltage represents the difference between the input and output position signals and is fed into the amplifier and switching device again. Thus the motor continues to drive the output position shaft while an error signal exists, and the motor turns the output shaft in a direction that will always decrease the error signal. The motor no longer develops output power when the difference between the input and output positions becomes zero.

Proposed position servomechanism.--A repulsion motor is the power member of the proposed system, and, since the motor must be reversible, two complete sets of brushes were installed. The motor can be controlled, if switches are connected across the brushes. A schematic diagram of this motor is shown in Fig. 2. If switch number one is closed, the motor will turn clockwise. If switch number one is opened, and switch number two is closed, the motor will turn counterclockwise.

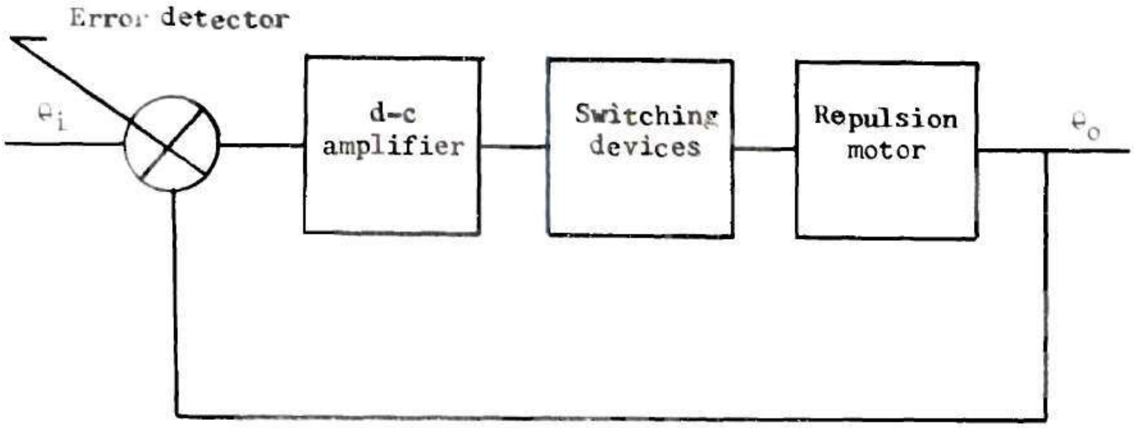


Fig. 1. Block Diagram of a Closed Loop Positional System.

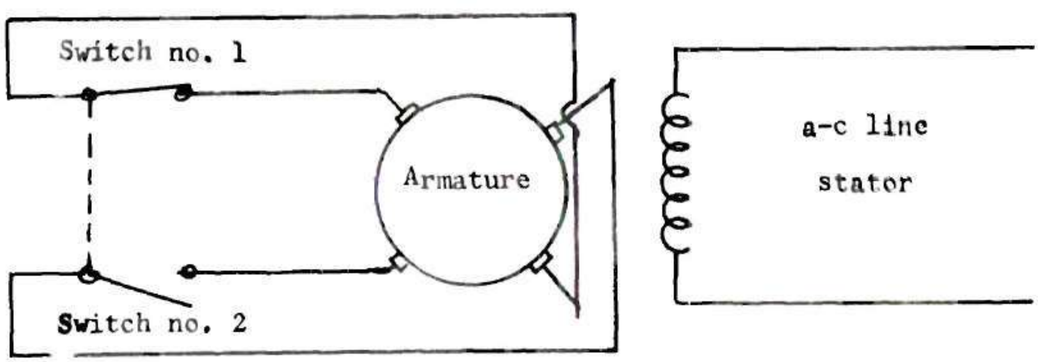


Fig. 2. Switch Control of a Repulsion Motor.

Instead of using two interlocked single pole single throw type switches as indicated in Fig. 2, grid controlled gas tubes (thyratrons) are used as the switching devices. A circuit diagram of one of the switching devices is shown in Fig. 3. The gas tubes are connected directly across the secondary of a transformer whose primary winding is connected to the brushes. The voltage drop across a gas tube is constant and is independent of the current flowing when the tube is conducting. Therefore, the circuit can simulate a short circuit. Being grid controlled, the tubes can be cut off, and the circuit can simulate an open circuit. Bias-shift control is used to control the grids of the thyratrons. If the d-c bias voltage is varied, the effective brush resistance can be smoothly varied.

If the a-c grid voltage is large (of the order of fifty or one hundred volts peak to peak), it can be assumed that the critical grid bias voltage is nearly zero. If the magnitude of the alternating grid voltage (which has been shifted by 90 degrees with respect to the anode voltage) is say fifty volts peak to peak, the tubes will be conducting for approximately a quarter-cycle per tube with zero d-c error voltage. If, in addition to the alternating voltage, minus fifty volts d-c is applied to the grids, the tubes will be cut off, and an open circuit will be simulated. If the polarity of the d-c voltage is reversed, the tubes will conduct a full half cycle per tube, and a short circuit will be simulated.

Two complete switching circuits are necessary to control the motor, and the two switching circuits are shown in Fig. 4. The d-c bias voltage is applied between the cathodes of the two sets of switching circuits. If a d-c bias voltage is applied, one set of tubes will be turned on while

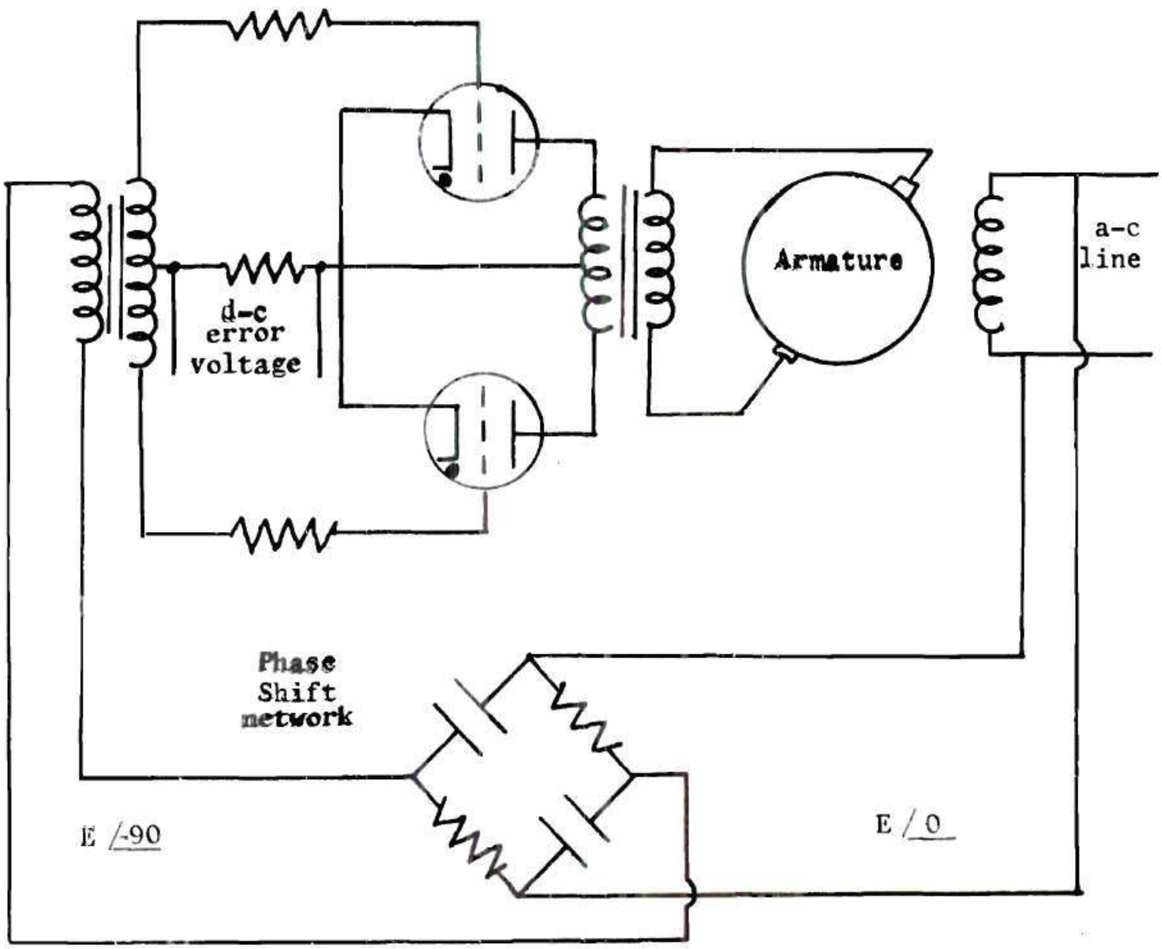


Fig. 3. A Switching Device for a Repulsion Motor.

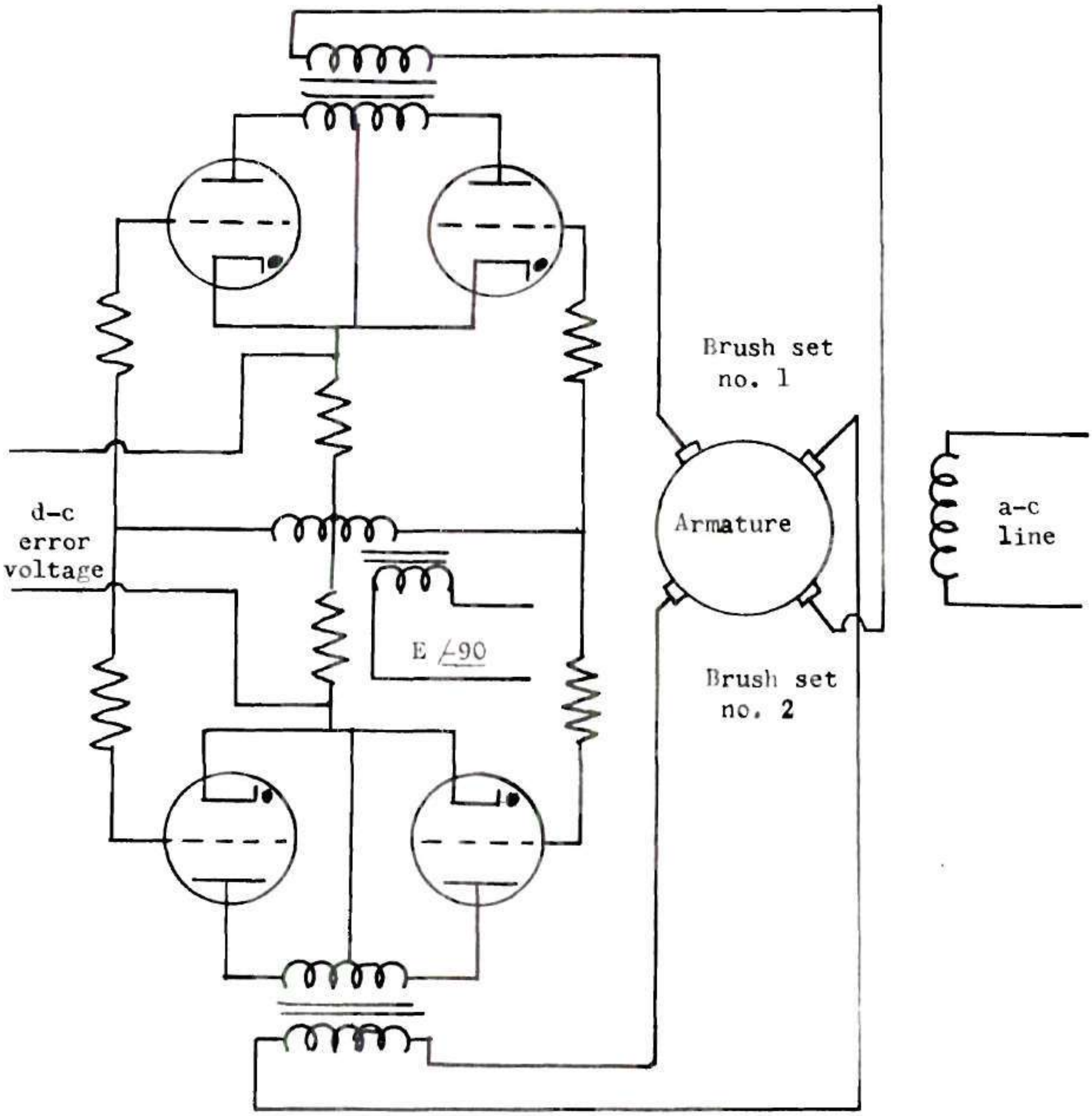


Fig. 4. Switching Circuits on a Repulsion Motor.

the other set is cut off. Therefore, the armature current can be smoothly shifted from one set of brushes to the other if the d-c bias voltage is gradually varied.

The combination of components of synchro generator, synchro control transformer, and discriminator forms the error detector system which transforms the position error of the servomechanism into a d-c error voltage. Fig. 5 shows a circuit diagram of the error detector.

It can be seen that the output of the control transformer is an a-c error voltage which is converted to a d-c error voltage in the discriminator. The reference voltage in the discriminator and the rotor supply voltage of the synchro generator are connected to the same alternating-current source.

The amplifier is added to provide sensitivity to the servomechanism. The circuit of the amplifier is shown in Fig. 6. It can be seen that the polarity of the output d-c voltage depends upon the polarity of the input d-c voltage.

The complete system composed of all the preceding components is shown in Fig. 7. All of the components connected together as shown form a complete closed loop system.

Operation of the system.--Assume the system of Fig. 7 initially is at rest. This means that the synchro generator, which is mechanically coupled to the motor shaft, is in a zero position relative to the synchro control transformer. No error voltage is generated, and, consequently, there is no total torque developed in the motor. The system is at rest.

Assume that the shaft of the synchro control transformer is rotated to introduce an error position between the generator and the control trans-

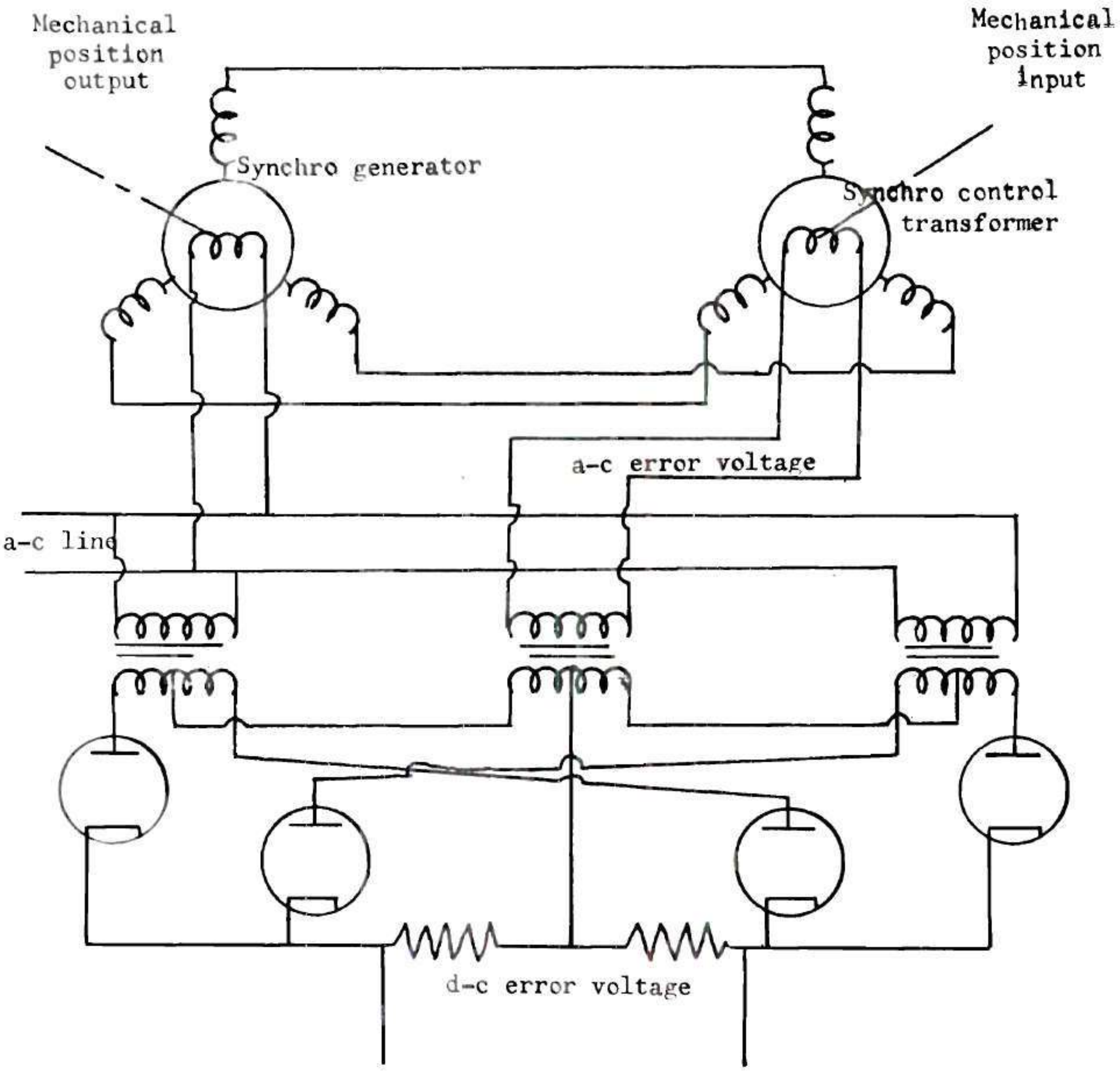


Fig. 5. Position Error Detector.

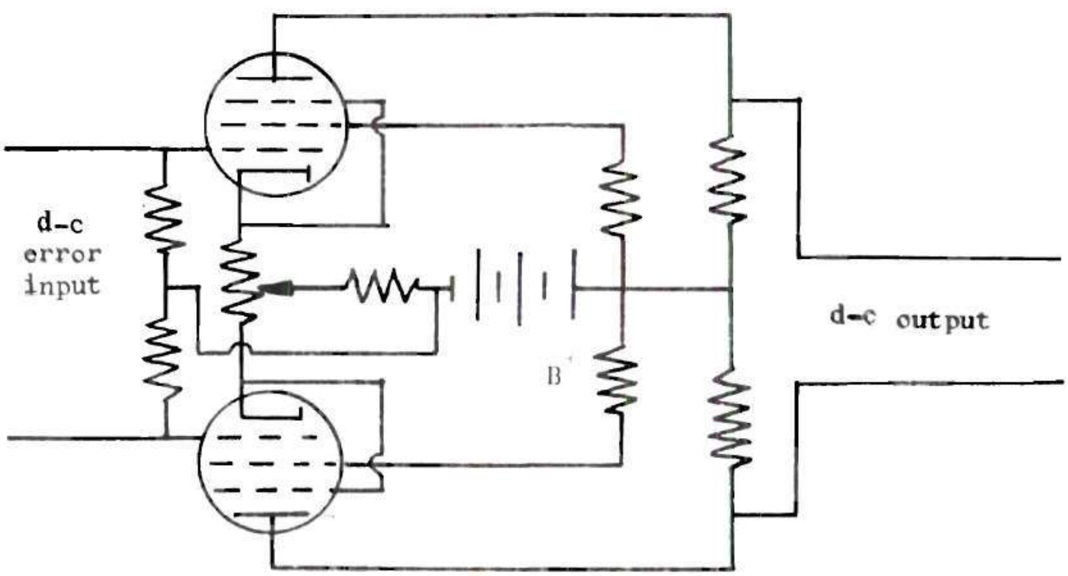


Fig. 6. A Polarity Sensitive d-c Amplifier.

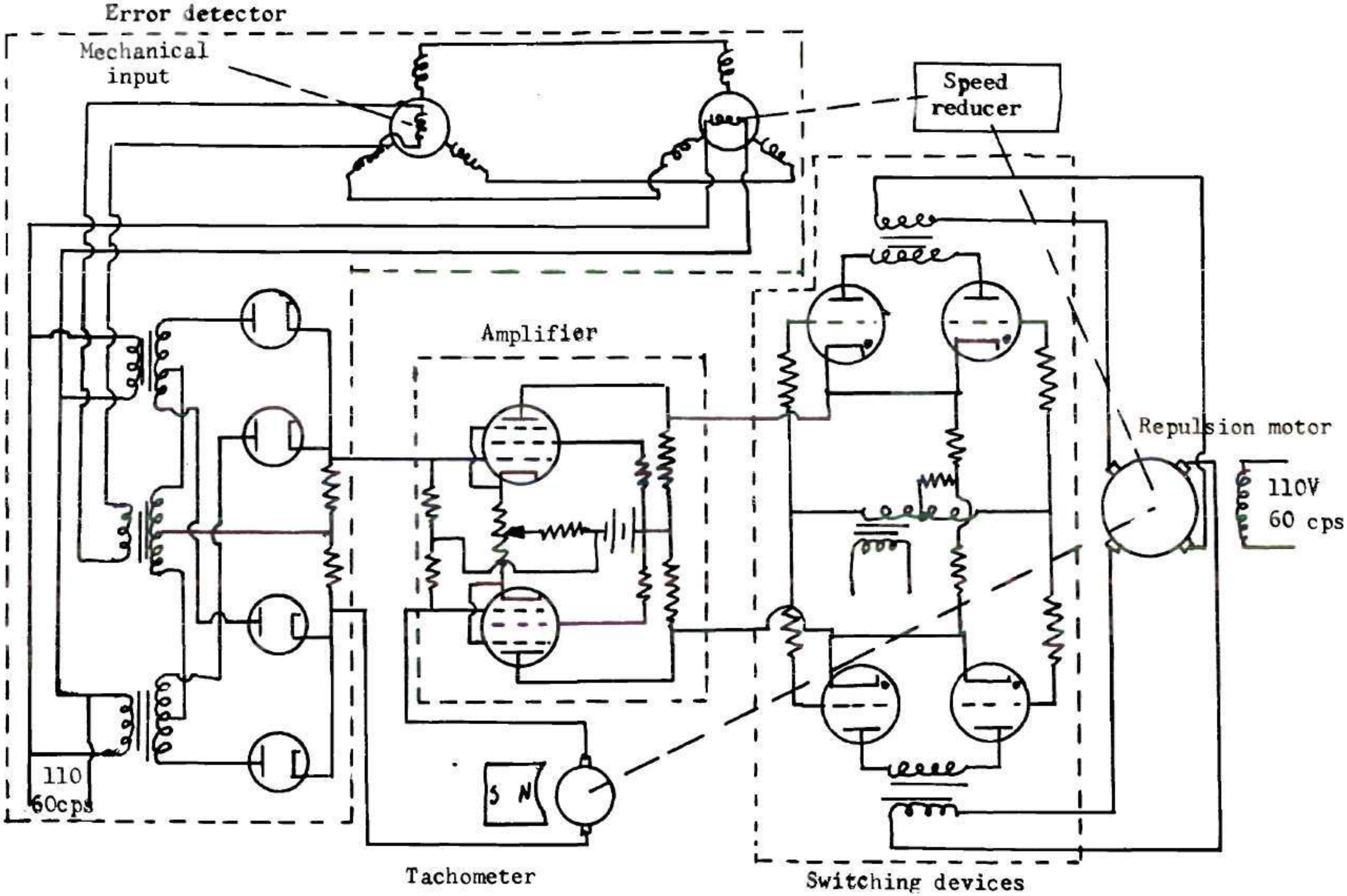


Fig. 7. Circuit Diagram of Servomechanism with a Repulsion Motor.

former, in the rotor of the latter an a-c error voltage is induced whose magnitude is determined by the magnitude of the error position. This a-c error voltage appears in the discriminator where it is converted into a d-c error voltage. The d-c voltage is fed into the tube grids of the amplifier where it is amplified, and the output is connected into the bias-shift control circuit of the thyratron gas tube circuits. This d-c bias voltage shifts the point of firing of both sets of tubes. One set of tubes increases its amount of conduction, while the other set decreases. The effect of this action is that the effective short circuit occurs over a larger portion of each cycle across one set of brushes, and the short circuit occurs for a shorter portion of each cycle for the other set of brushes. The torque developed by the former set of brushes is increased in its amount, while the torque developed by the latter set is decreased. The total torque developed in the motor is in a direction determined by the former set of brushes. The armature rotates and the rotor of the synchro generator also rotates as it is mechanically coupled with the motor through a speed reducer. Rotation of the armature continues until the error position of the generator-control transformer network becomes zero. At this point no torque is developed in the motor. However, inertia in the system may cause the motor and synchro generator to continue to turn past the null position. The a-c error voltage is then shifted in phase by 180 degrees. The polarity of the d-c error voltage in the discriminator, amplifier, and bias-shift control circuit is reversed. The effective short circuit is shifted from the first set of brushes to the second set and torque is developed in the proper direction to again bring the synchro generator to the null position. The above process continues until the system again settles down to rest.

CHAPTER III

DESIGN AND CONSTRUCTION OF EQUIPMENT

A modified repulsion motor.--The motor which was available for this project is rated at one third horsepower, 110 volts, 1725 revolutions per minute, and was originally built as a repulsion start-induction run type of motor. However, the centrifugal switch, which enabled the motor to operate as an induction run motor, was removed.

The motor of the proposed closed loop positional system must be reversible, and this was accomplished with two complete sets of brushes as previously described. The particular motor available for this project is a four pole machine. Since there are usually two brushes in a set per pair of poles, the four pole machine requires a total of eight brushes.

In each particular set, the four brushes are installed with one located each 90 degrees around the periphery of the commutator. The brush holders are installed so that they are insulated from each other, although the opposite, or 180 degree brushes will be connected together.

Since repulsion motor characteristics are very sensitive to a variation of brush position relative to a neutral axis, the brush holders must be constructed so that the brush position can be adjusted. It is desired that the motor have equal operating characteristics when it is running in either direction; therefore, each set of brushes must be adjustable independently of each other.

The brush rigs for mounting the brush holders of both sets of brushes are shown in Fig. 8. The geometry of the brush holders for sets

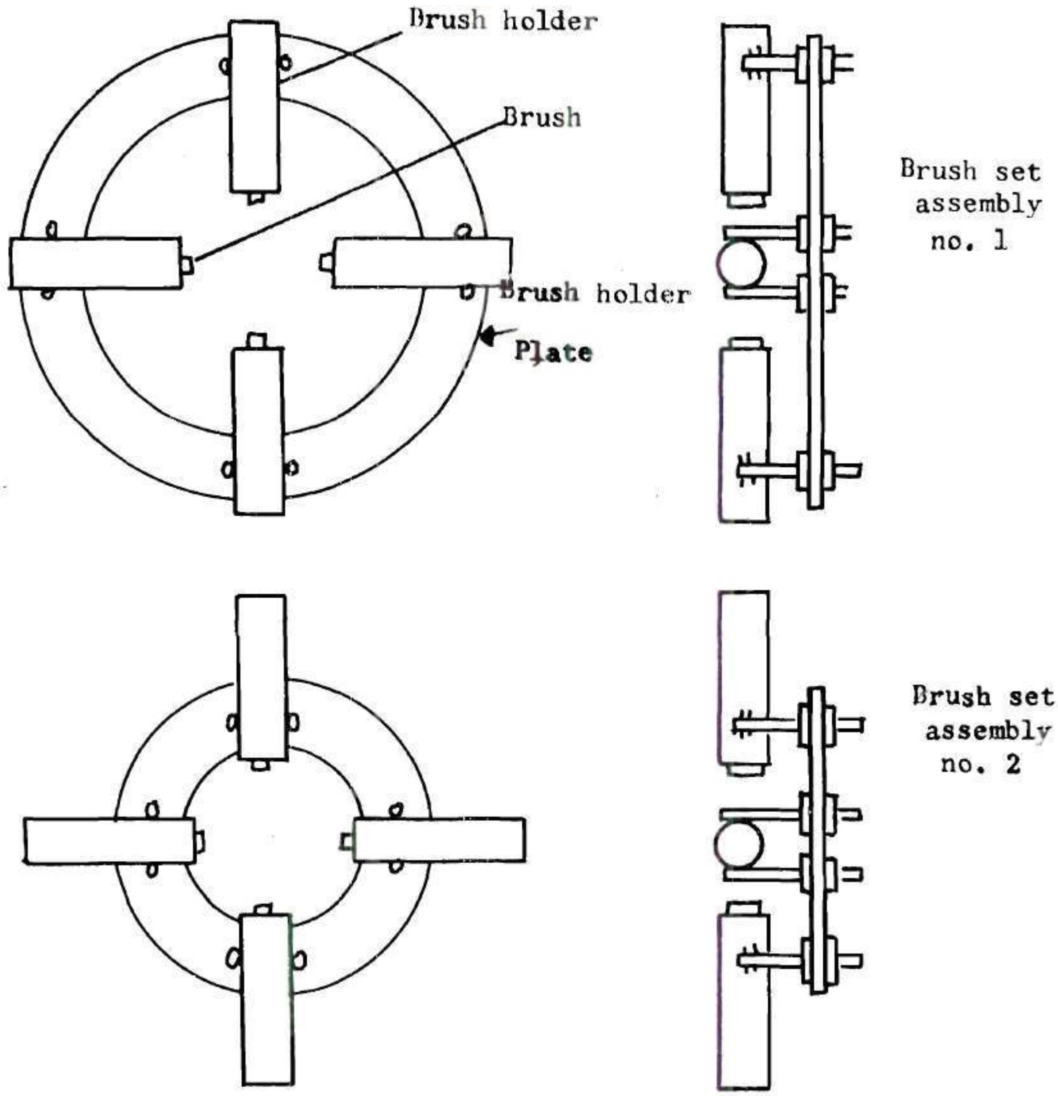


Fig. 8. Brush Set Assemblies Nos. One and Two.

number one and two are identical, i. e., there are four brush holders on each rig, the holders being 90 degrees apart, and the brushes will fit the same size commutator. The brush holders are made of a material that can be soldered. Copper bolts were soldered to the brush holders which were then bolted to the brush holder plates.

A frame for mounting the brush holder plates is shown in Fig. 9. Four bolts are mounted on this plate. The outside diameter of a circle enclosing these bolts is identical to the inside diameter of the brush holder plate of brush set number one. The inside diameter of a circle just touching the bolts is identical to the outside diameter of the brush holder plate of brush set number two.

When both sets of brush-holder plates are mounted on these four bolts, they form a set of bearings about which the brush sets can be rotated. The complete assembly is shown in Fig. 10. The frame shown in Fig. 9 is the part of the assembly which is fastened to the end bell of the motor. Thus it can be seen that with the commutator in place (and within certain limits) the two sets of brushes can be adjusted separately.

Gas tube switching device.--Gas tubes are used as the switching devices for the proposed servomechanism. It is possible to switch a very low resistance from one set of brushes to the other with thyratron tubes in a sudden switching action. However, it is desirable in this servomechanism to switch the load gradually from one set of brushes to the other. This feature will be accomplished by a gas tube circuit.

Fig. 11 shows a full wave gas tube rectifier with a short circuit installed in the place of a load resistance. The tubes are fired by the bias-shift control method, and the point of firing at any point in a cycle

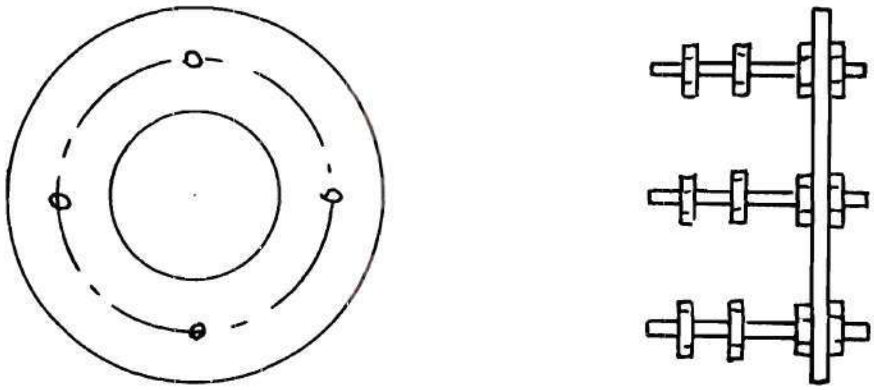


Fig. 9. Brush Set Mounting Frame.

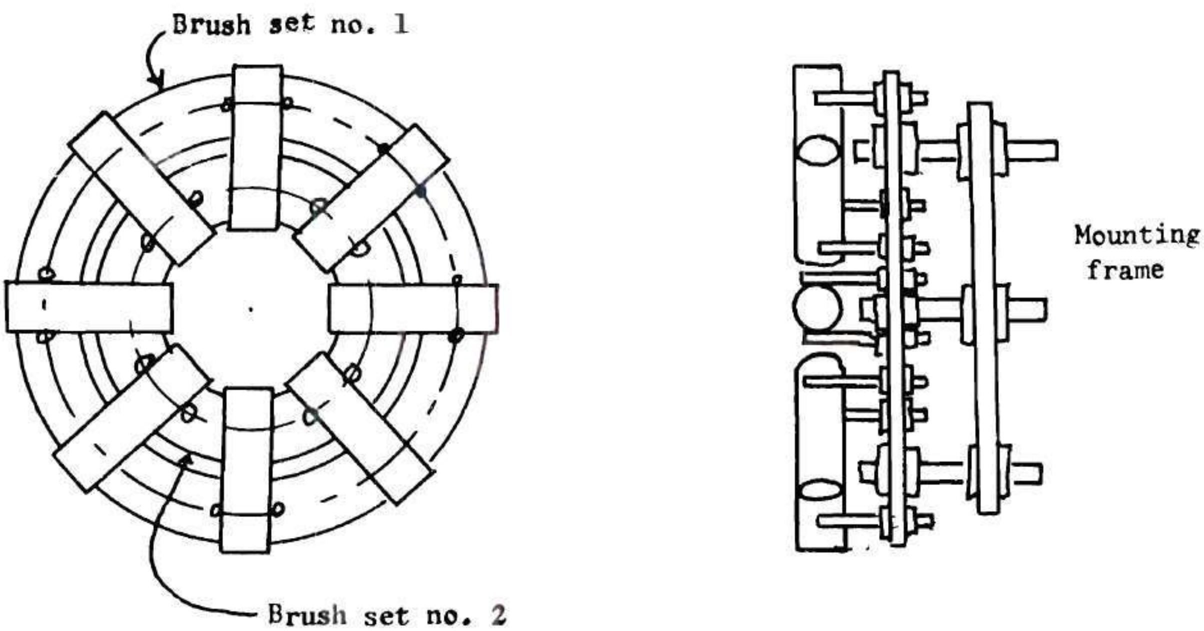


Fig. 10. Complete Brush Assembly.

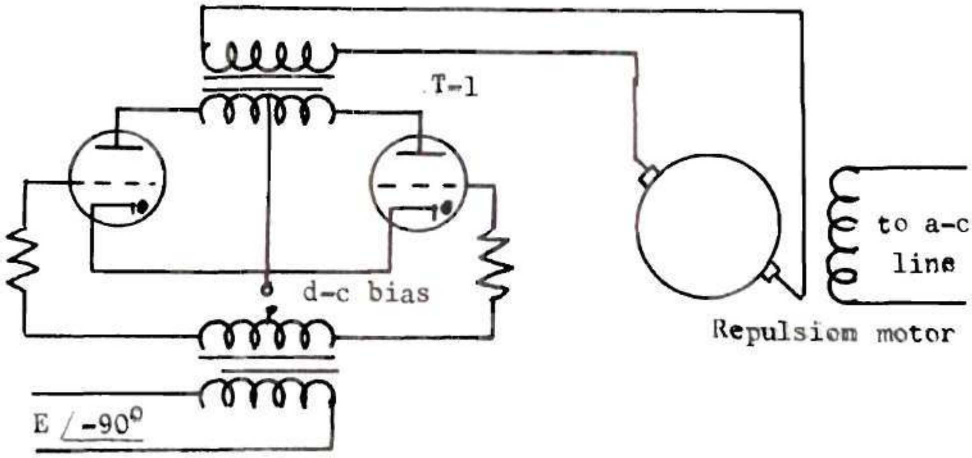


Fig. 11. Full Wave Rectifier.

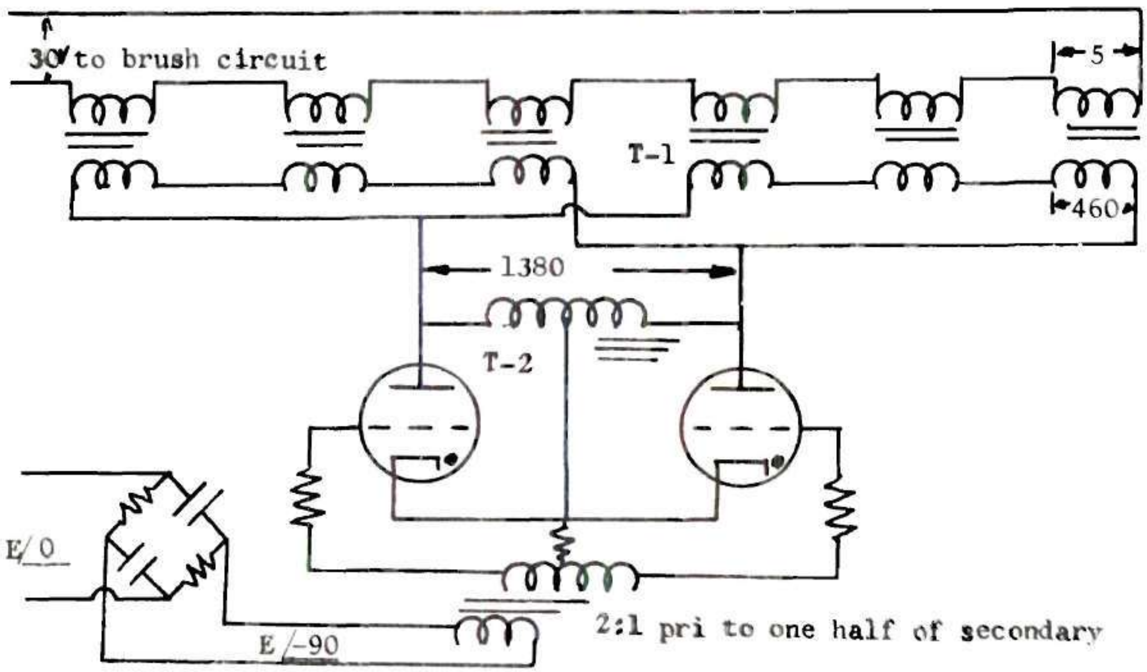


Fig. 12. Short Circuited Full Wave Rectifier.

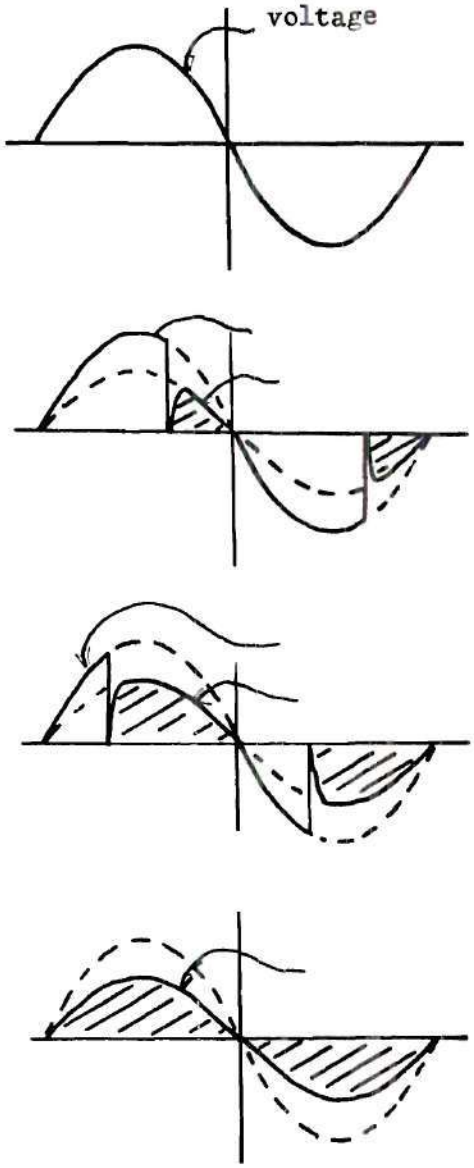
can be accomplished as desired.

The line voltage, which is applied to the stator of the repulsion motor, is sinusoidal: therefore, the induced voltage in the rotor is approximately sinusoidal. If the brushes are short circuited, the voltage becomes small, and the wave form of the current is sinusoidal.

The gas tubes are connected directly across the secondary winding of the transformer T-1. If each tube fires over 180^{o} of its positive half cycle, the voltage across the secondary of transformer is the voltage drop of the tubes which is approximately a constant value, and the current becomes a sinusoidal wave. If the tubes do not fire at all, the voltage is sinusoidal, and there is no current. These same wave forms appear across the primary (or brush side) of transformer T-1.

When each tube begins its firing cycle at some time between 0 degrees and 180 degrees in the positive half cycle, the voltage and current waveforms are affected. Some wave forms of this nautre are shown in Fig. 13. The wave form is shown with the tubes not firing in (a). In (b) each tube fires over 60 degrees in the positive half cycle. In (c) each tube fires 120 degrees of the cycle. And in (d) each tube fires 180 degrees of the cycle. It can be seen that the voltage is sinusoidal until the tubes begin firing, then the voltage drops to zero. At that point the current begins flowing and assumes a sinusoidal wave form for the remainder of the cycle. Hence the short circuit on the brushes can be forced to occur at any point in a cycle, and various degrees of torque can be developed depending upon the point of firing of the tubes.

Preliminary tests on the motor indicated that approximately fifteen amperes could be expected when the brushes are short circuited and



(a) Tubes not firing.

(b) Each tube fires for 60°
of the cycle.

(c) Each tube fires for 120°
of the cycle.

(d) Each tube fires for 180°
of the cycle.

Fig. 13. Voltage and Current Waveforms Across
Brushes of a Repulsion Motor.

approximately forty volts would appear across the brushes when they are open circuited. These tests were made with the brushes in their optimum position. The gas tube circuit was designed to handle these current and voltage characteristics.

The gas tubes used in this project are thyratrons (FG-17) whose capacities are one half ampere as their average current and twenty-five hundred volts for their peak inverse voltage.

A full wave short circuited rectifier is shown in Fig. 12. Transformer T-1 is made up of six small transformers. The voltage ratio of the small transformers is five volts to four hundred and sixty volts. Since the magnitude of the brush voltage is about thirty volts, the five volt primary side of each of the six transformers is connected in series. No center tap can be made in the secondary of transformer T-1, because in a full wave rectifier only one tube conducts at any given time. The result would be that no current would flow in the secondary circuits of the transformers associated with the tube that is not conducting at the time. Hence a large inductance would appear across the primary side which would limit the amount of current that could flow in any of the primary circuits. Thus a center tapped auto transformer, number T-2 in the figure is used to construct a satisfactory full wave rectifier.

If the effective value of current in a thyratron of Fig. 12 is one-half of an ampere, this current appears in one-half of the leg of the auto transformer T-2. Since the current flowing in that part of the auto transformer is one-half of an ampere, the current flowing in the secondary of the transformer T-1 is one fourth of an ampere. There are two thyratrons; therefore, the total current in the secondary of T-1 is one-half ampere.

Transformer T-1 was connected so that its turns ratio was

$$N = \frac{1380}{30} = 46$$

When one half of an ampere flows in a thyratron, the current in the primary of T-1 is

$$I_{sc} = N \times 0.5 = 23 \text{ amperes}$$

which is the current that will flow in the brush circuit.

If the maximum electric potential of the brushes is forty volts, then it can be seen that

$$V = N \times 40$$

$$V = 46 \times 40 = 1840$$

The peak value of this voltage is

$$1840 \sqrt{2} = 2630$$

and the peak inverse voltage across the tubes will be 2630 volts. This value approximates the peak inverse voltage capacity of the tubes. This ratio of 46 was verified experimentally to satisfy the current and voltage requirements of the circuit. Two circuits are necessary, of course, since there are two sets of brushes.

A resistance-capacitance bridge is used to obtain an alternating grid voltage which is approximately 90 degrees lagging in phase to the brush circuit or anode voltage. Large grid resistances of the order of 10,000 ohms were found necessary to keep the phase shift of this voltage constant since grids of the thyratrons draw currents and introduce a resistance load across the phase shift bridge.

Amplifier.--The circuit diagram of the amplifier used in the proposed system is shown in Fig. 14. The bias-shift resistors R_1 and R_2 of the thyratron rectifier circuits actually forms a load resistance on the two amplifier tubes. These resistors are made large in value compared to the normal tube load resistors so as to decrease their effect on the amplifier tubes. A d-c voltage applied across R_2 with the negative polarity toward the grid transformer will drive both sets of grids negative with respect to their cathodes. This resistor with a certain constant d-c voltage applied can furnish a fixed bias for both sets of thyratrons.

A d-c voltage applied across resistor R_1 will cause the grids of one set of thyratrons to be negative with respect to the cathode while the grids of the other set will be positive. If the polarity of this d-c voltage is reversed, the grid voltage with respect to the cathode of each set of tubes will also be reversed.

Since the amplifier is polarity sensitive, the polarity of the output d-c voltage is reversible. Therefore, the current conduction in the thyratron circuits can be switched from one set of tubes to the other.

Error detector.--The synchro generator is geared to the motor with a ten-to-one ratio. A d-c tachometer is attached to this gear train with a one-to-one ratio with the motor.

The control transformer provides an a-c error signal whose magnitude depends upon the magnitude of the position error, and the discriminator converts this a-c voltage to a d-c voltage. The tachometer provides a d-c voltage whose magnitude is proportional to the speed of the motor.

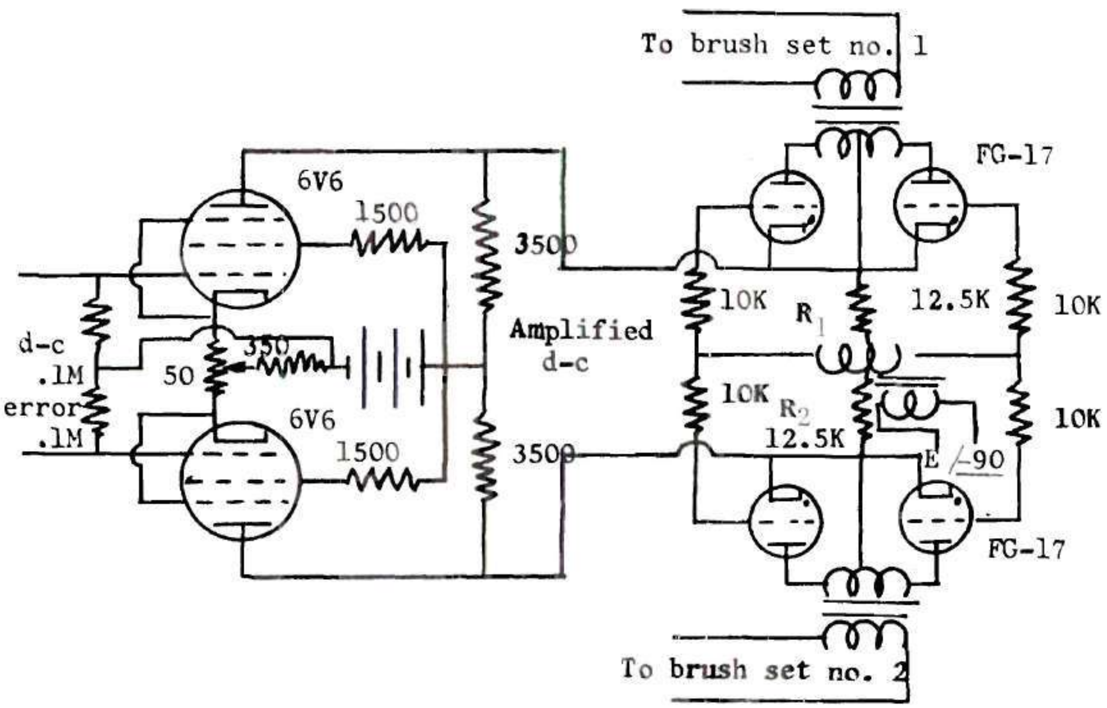


Fig. 14. Polarity Sensitive Amplifier Coupled to Two Rectifier Circuits.

This tachometer voltage is connected in series with the d-c error voltage from the discriminator and fed into the input of the amplifier.

The effect of the tachometer is to provide a damping torque on the system. When the motor is running, the tachometer produces a d-c voltage whose effect is to provide a reverse torque on the motor. This reverse torque is proportional to the motor speed and disappears when the motor is at rest. The tachometer tends, therefore, to stabilize the closed loop system by providing output derivative control.

Power saving device.--After the system was completed and placed in operation, tests showed that it absorbed too much power with the motor at rest. Since the system is designed to be a positional device, it is anticipated that long periods of time would lapse with the motor sitting at rest. To economize the power which would be lost during these periods, a circuit was designed to automatically turn the system off.

The turn-off circuit is shown in Fig. 15. The phase of the grid alternating voltage is adjusted so that the tubes either fire all of the time or none of the time. Thus the transformer T-1 is either short circuited or open circuited at all times.[1] A small d-c error voltage will cause the thyratrons to fire one hundred per cent of the time.

The a-c error voltage of the control transformer is fed into an a-c amplifier. The a-c output voltage is fed into a twin cathode follower circuit whose output is a d-c voltage. This d-c voltage becomes the bias for the thyratron rectifier circuit.

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[1] It is open circuited in the sense that the inductance sufficiently great to prevent any appreciable current to flow when the secondary has no current flowing. It is short circuited in the sense that the conducting thyratrons short circuit the secondary.

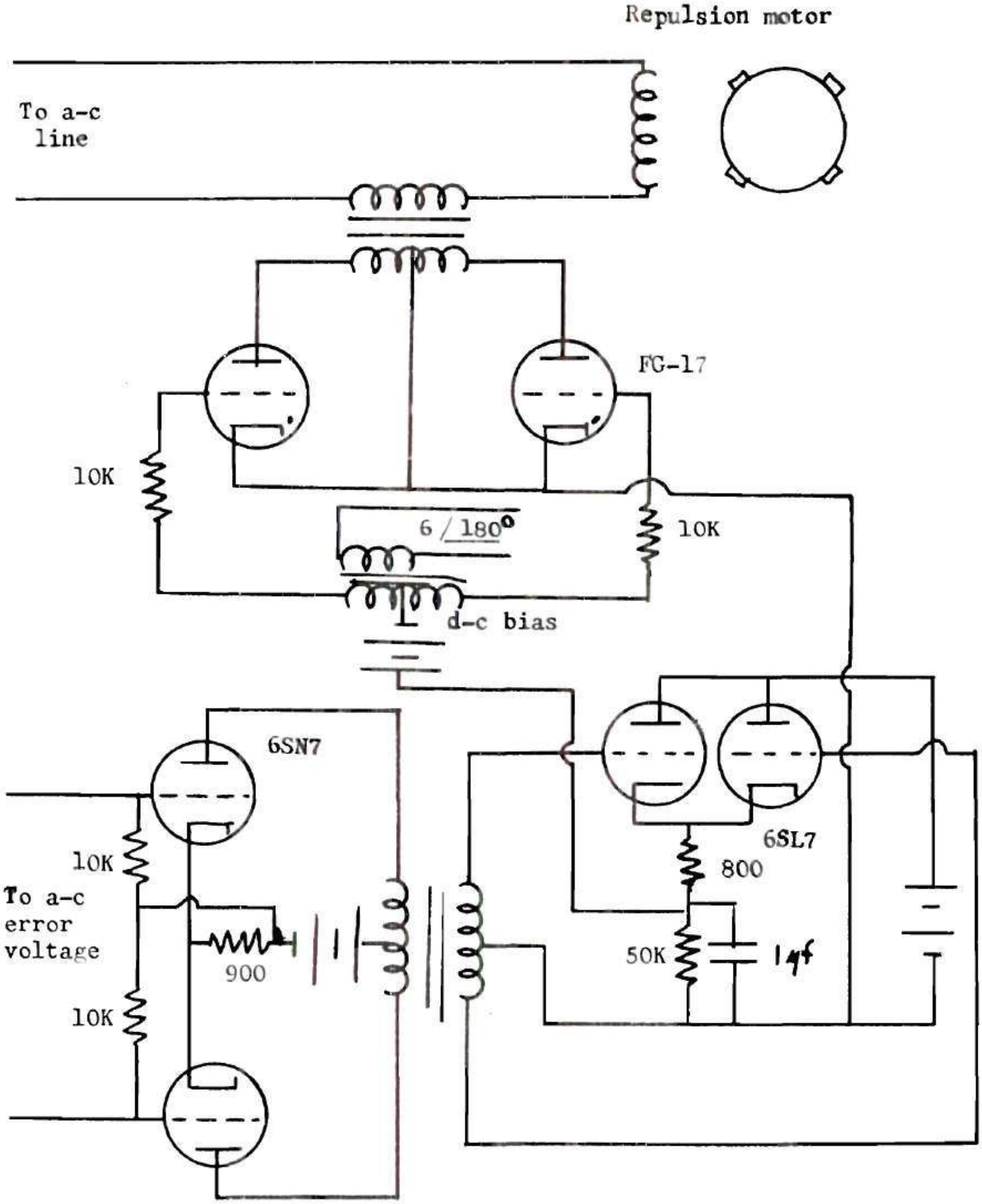

Fig. 15. Circuit of an Energy **Saving Device.**

As long as there is an a-c error voltage from the control transformer, a d-c voltage appears across the cathode follower output, and the thyratron circuits are forced to conduct at all times. The system, under these conditions, is excited. But if there is no a-c error voltage, and the system is at rest, the d-c voltage across the cathode follower output falls to a certain adjusted value, and the tubes cut-off. Thus the system is at rest and little power is absorbed by the system.

Photographs of the completed closed loop system are shown in Fig. 16.

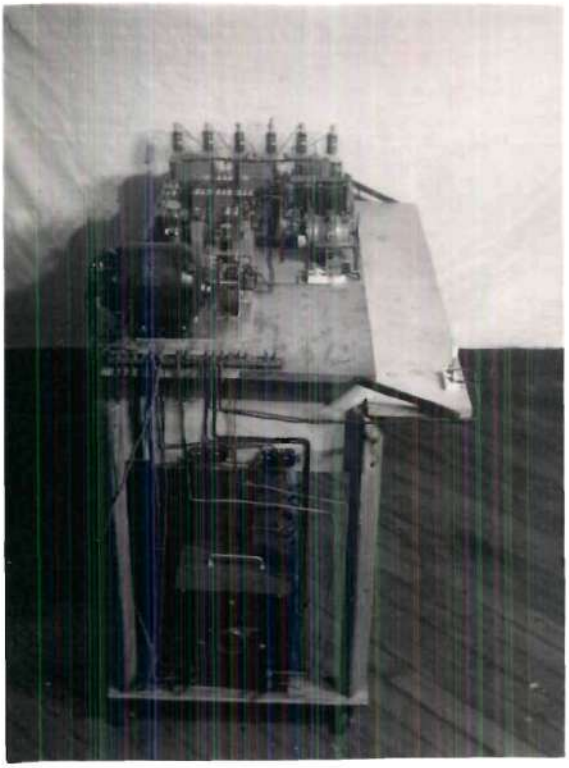

Fig. 16. Photographs of the Completed Servomechanism

CHAPTER IV

PERFORMANCE OF THE FINAL SYSTEM

Starting torque and power absorbed versus brush position of a straight repulsion motor.--Starting torque of the motor for the proposed system is found by use of a lever arm which is rigidly attached to the motor shaft at one end and is supported by a set of scales at the other end. All measurements are taken when the lever arm is horizontal.

The position of the brushes is completely adjustable as can be seen in the design of the brush sets described in Chapter III. A test is made with only one set of brushes in place. The other set is disconnected and the brushes lifted from the commutator. The brush position is varied from the neutral axis to the line of the poles. This test gives starting torque versus brush position for a straight repulsion motor. Several magnitudes of error signals were introduced into the system and measurements are made for each value of error voltage. To prevent a variation of error signal which will occur when the motor turns slightly, the synchro generator was disconnected from the motor shaft. In this test, voltage, current and power measurements are made across both the input to the motor and across the brushes. Results of these tests are shown in Tables 1 to 8 in the Appendix.

Starting torque and power absorbed versus brush position of the modified repulsion motor.--With both sets of brushes in place, the characteristics of the repulsion motor is expected to be very slightly different from that of a straight repulsion motor.

Starting torque, voltage, current, and power measurements are made in a manner similar to that previously described. This time both sets of brushes are adjusted to equal positions opposite the neutral axis. Because of the size of the brush holders, certain brush positions could not be obtained. In other words, it would be impossible to install both sets of brushes (for this particular design of brush holders) along the neutral axis at the same time. Other possible positions were obtained and tested.

Fig. 17 reveals maximum starting torque versus brush position. The greatest torque is approximately 570 ounce-inches where the brushes are located at approximately thirty mechanical degrees from the neutral axis for this four pole machine. The torque decreases to zero, of course, with the brushes at zero or at forty-five mechanical degrees.

The maximum power used by the machine is illustrated in Fig. 18. The least power is used with the brushes along the neutral axis. The power increases quickly as the brushes approach the thirty mechanical degrees point (where maximum torque occurs), then gradually increases further as the brushes are moved to the forty five mechanical degrees point.

Figs. 19 and 20 show torque versus degrees error for various brush positions. The wavy lines give somewhat inconclusive characteristics of the motor for various degrees error. The torque measurements for certain degrees error were difficult to make. If the motor turned very slightly so that the brushes made contact with a new commutator segment, the torque measurements would be affected. And this change in torque would be appreciable since the machine is very sensitive to brush position.

The torque is rationalized as a fraction of total torque, and curves of rationalized torque versus degrees error for three brush positions are

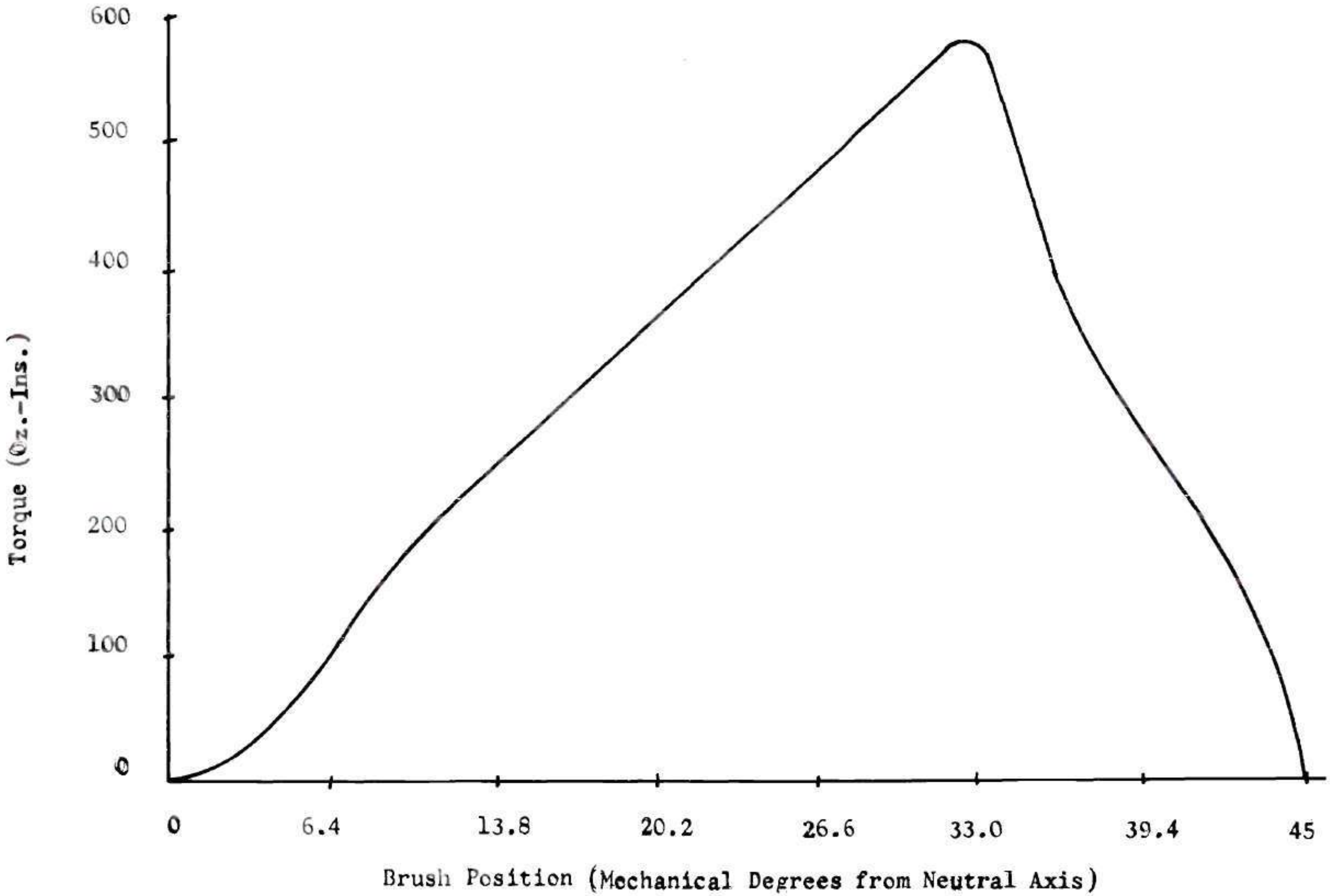

Fig. 17. Maximum Torque Versus Brush Position for a Straight Repulsion Motor.

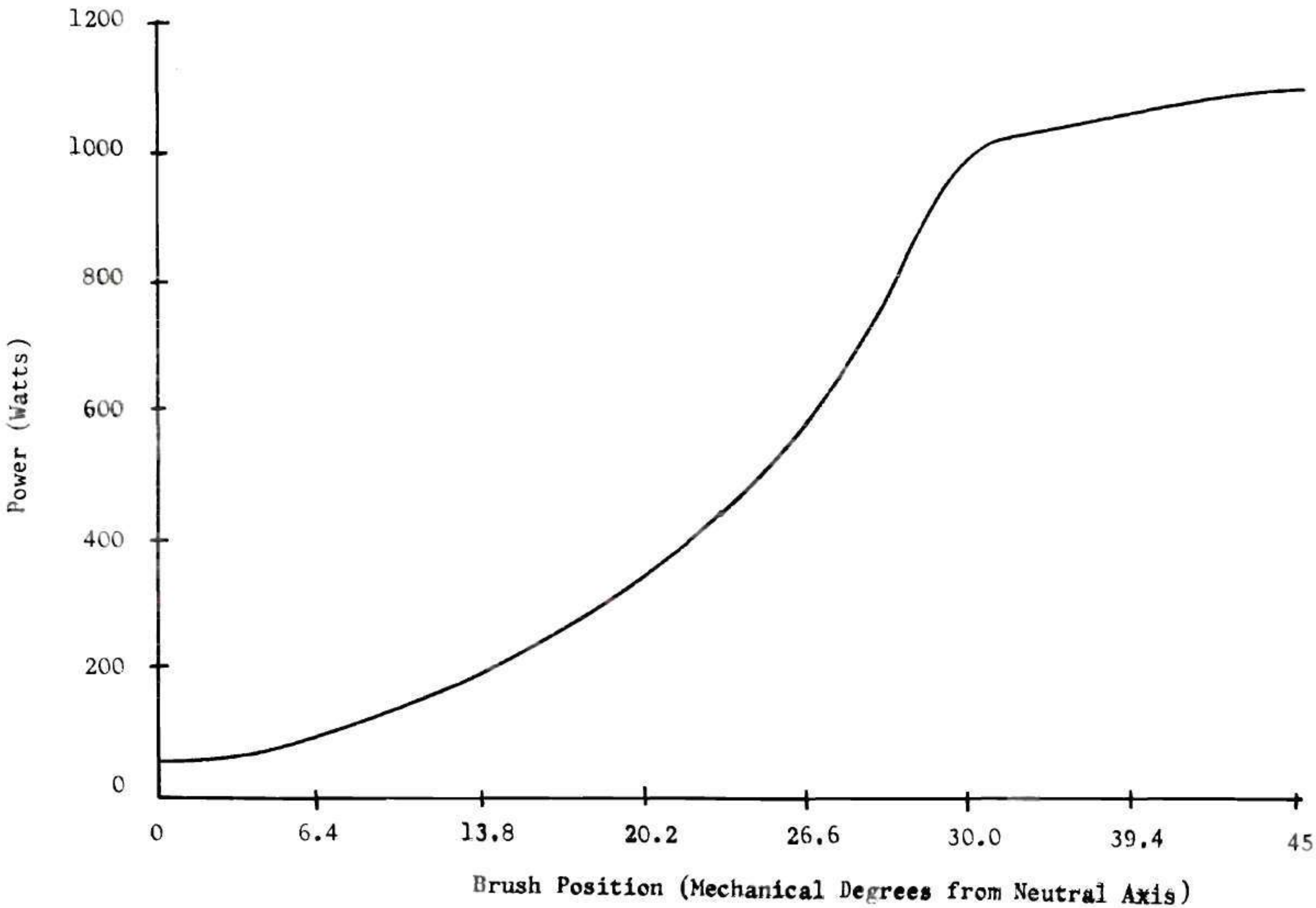

Fig. 18. Maximum Power Absorbed by Motor Versus Brush Position for a Straight Repulsion Motor.

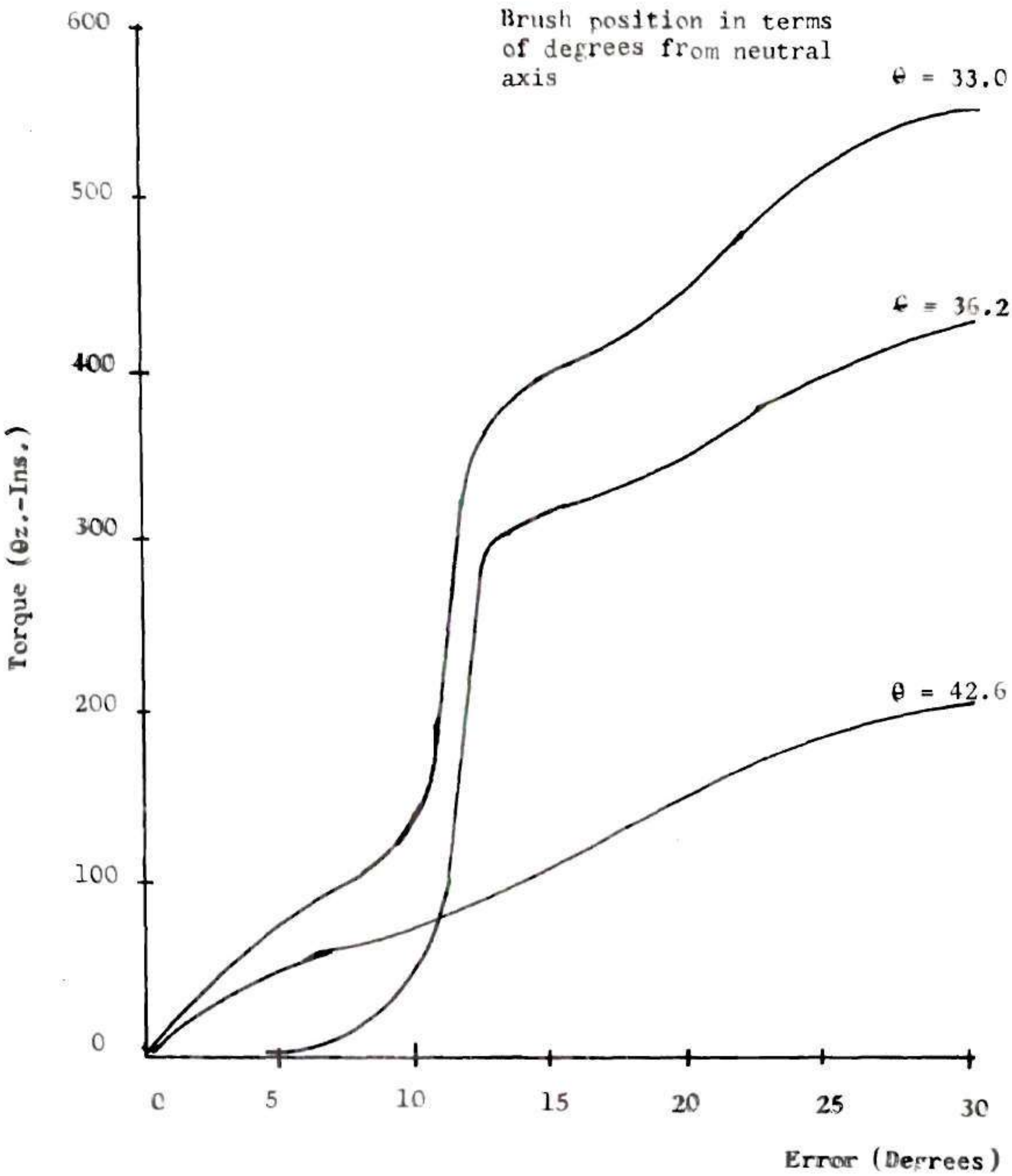

Fig. 19. Curves Showing Torque Versus Degrees Error for Various Brush Positions for a Straight Repulsion Motor.

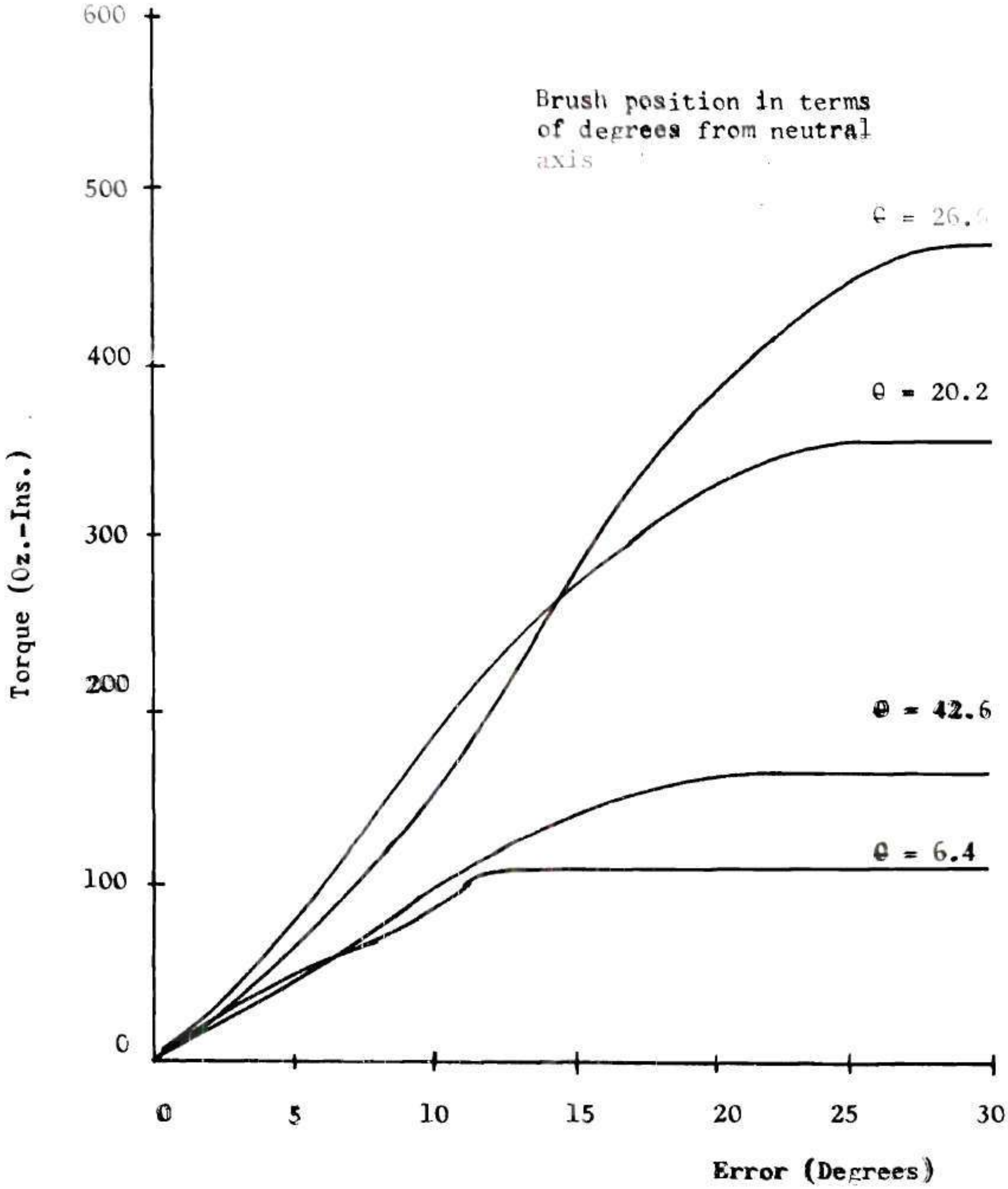

Fig. 20. Curves Showing Torque Versus Degrees Error for Various Brush Positions for a Straight Repulsion Motor.

shown in Fig. 21. This figure indicates that the torque is developed more rapidly as the error increases for the smaller angles of brush position. In other words, when the brushes are adjusted to the point where a maximum magnitude of starting torque is small, this total torque can be developed with a very small change in error. This characteristic can be looked upon as gain in the servomechanism. An increase in gain will occur when the brushes are adjusted to a position of low starting torque. Lower gain in the motor occurs when the brushes are adjusted for higher starting torque.[1]

Equipment and arrangements for making frequency response tests.--If an input positional disturbance is introduced into the synchro generator of a positional servomechanism, the system becomes excited, and the shaft of the synchro control transformer is forced by the system into correspondence with the input shaft. For frequency response tests, the input shaft is given oscillating movements in a sinusoidal fashion. This means the input shaft is rocked in each direction so that its change in angular position represents a sinusoidal input signal. The output member of the system will also oscillate in obedience to the command of the input signal, but the magnitude and phase of the output will probably be somewhat different from that of the input. Thus, the frequency response test consists of introducing a sinusoidal input to the servomechanism and noting the output of the system.

When the input shaft of the synchro generator is sinusoidally oscillated, the error signal at the input to the discriminator is a voltage

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[1]The author's experience with the proposed servomechanism reveals that the system is much less stable when the brushes are adjusted near the neutral axis than when they are adjusted for high starting torque.

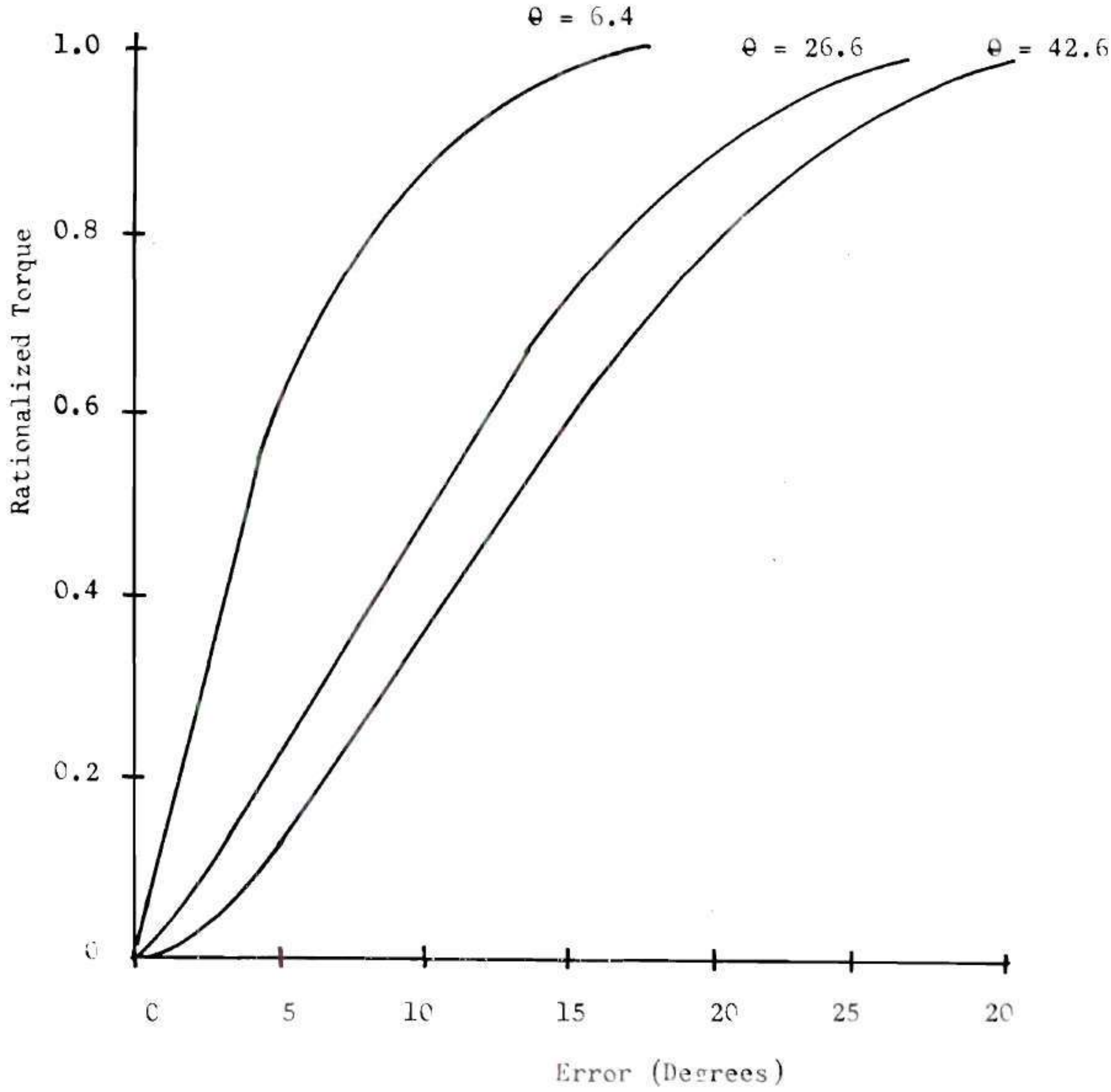

Fig. 21. Rationalized Torque Versus Degrees Error for Three Brush Positions.

which represents this motion. The wave form of the signal is shown in Fig. 22. The voltage is a sinusoidally modulated wave with carrier suppressed. The carrier signal is 60 cycle alternating voltage and the modulating voltage varies the carrier in a sinusoidal manner. The carrier frequency voltage is not constant, but, instead, changes its phase by 180 degrees each one half cycle of the modulating signal. This type of modulation is called suppressed carrier modulation.

A wave form like that shown in Fig. 22 may be obtained from a synchro generator by first exciting the rotor with a sixty cycle current and then continuously rotating the shaft at the same frequency of the desired modulated signal. In making the frequency response test, the system will be excited by a signal obtained in this manner rather than oscillating the control transformer shaft of the input to the system.

The equipment and arrangements for measuring the phase shift between input and output signals is shown in Fig. 23. For the input signal a synchro generator is mechanically coupled with a variable-speed drive motor. The stator windings of the generator are connected with the stator windings of a synchro control transformer whose rotor is blocked. The rotor of the generator is connected to a variable alternating current supply, while the rotor of the control transformer is connected to the input of the servomechanism. Therefore, when the generator rotor is excited with an a-c voltage and is rotated at a continuous speed, the signal from the control transformer rotor is a modulated sinusoidal wave such as that shown in Fig. 22. This wave in its demodulated form represents a sine wave input to the servomechanism of the same frequency as the angular frequency of the rotating armature of the synchro generator. The voltage wave form between

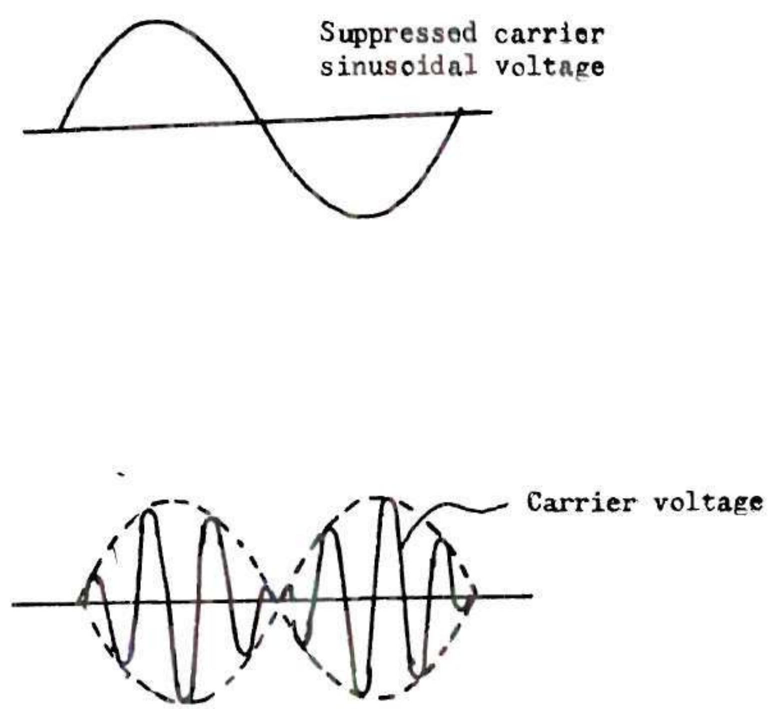

Fig. 22. Modulated Sinusoidal Wave.

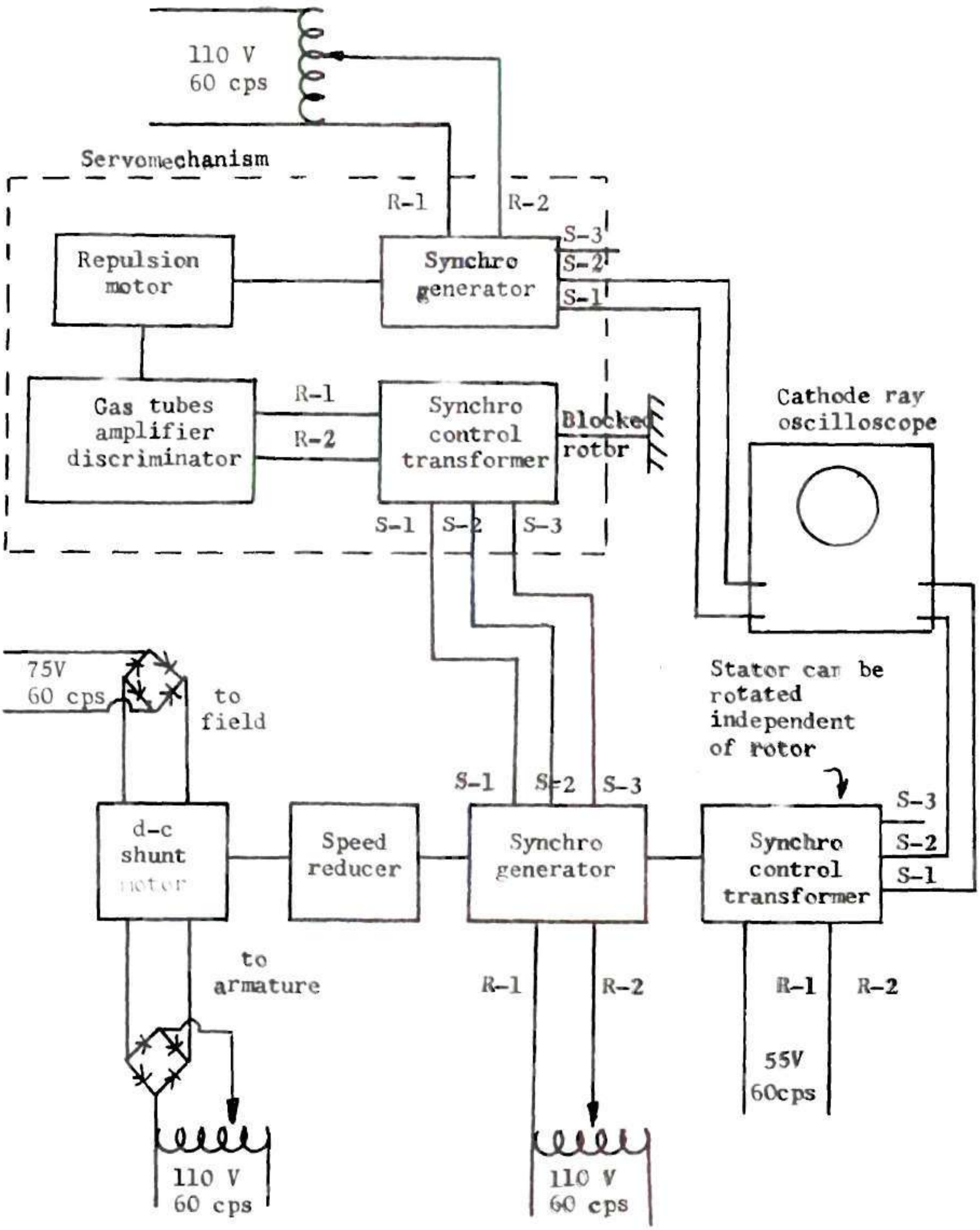

Fig. 23. Equipment and Arrangements for Performing Open Loop Frequency Response Tests.

any two stator windings of the synchro generator is similar, at this point, to the waveform of the control transformer rotor except for the phase relation. Actually, the signal between stator terminals could be used just as well as that from the rotor of the control transformer to oscillate the system; however, the control transformer will be used at a later time to align the system.

In Fig. 23 the output appears as angular movement in a second synchro generator which is mechanically connected to the drive motor of the servomechanism. With an a-c voltage applied to the rotor of the generator, the voltage wave form across any two stator terminals is similar to the waveform of the input signal.

With the system at rest the control transformer can be used to line up the output to a phase relation with the input. An oscilloscope can be connected with the horizontal plates across two stator terminals of one generator and the vertical plates across the same relative stator terminals of the second generator. When the system is operating, it can be seen on the osclloscope screen that the output signal lags, by some phase angle, the input signal.

A second control transformer was mechanically coupled to the generator which produces the input signal. This control transformer was mounted so that the stator could be rotated independently of the rotor. When an a-c voltage is supplied to the rotor, a signal appears across two terminals of the stator which is similar to the signal across the generator. Since the stator is movable, the phase of the control transformer signal can be shifted relative to the phase of the generator. Thus, this signal can be adjusted to be in phase with the generator stator signal.

As was mentioned previously, an oscilloscope connected across both relative stator windings of the two generators illustrates two signals which are out of phase. The same picture is seen when the stator winding of the control transformer replaces the same relative stator windings of the former which'can be adjusted to be in-phase with the latter.

The phase between the input signal and the output signal can be measured directly by rotating the stator of the control transformer until the figure on the oscilloscope indicates that the two signals are in phase. The phase difference is merely the number of degrees that the stator of the control transformer is turned.

With a signal from the control transformer and from the output generator connected into the oscilloscope, various figures and shapes can be seen on the screen when the system is operating. An accurate interpretation of the figures is necessary to assure correct reading of the phase difference between the input and output signals.

The frequency of the signals is variable and is less than two cycles per second, and the frequency of each signal is identical.[2] Also these two voltages exist on a sixty-cycle carrier frequency. This carrier frequency of each signal is always either in phase or one hundred and eighty degrees out of phase.

Because of the sixty-cycle voltage of each signal which is always in like phase, a straight line will appear on the screen regardless of the

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[2]In this open loop test, the output frequency, as it appears in a stator winding of the synchro generator, can be greater than the input signal. The frequency remains the same so long as the magnitude of the input signal does not drive the position of the generator more than one hundred and eighty degrees.

phase. If the phase of the two signals is different by ninety degrees, and their magnitudes are equal, a straight line appears on the screen whose entire length rotates at the modulation frequency of the signals. In this case the length of the line remains constant. If the magnitude and phase of both signals are equal, a straight line appears on the screen which is inclined at a 45 degree angle with the horizontal. This line converges on itself oscillating between a maximum value and zero at the modulation frequency of the signals.

A system for measuring the magnitude of the input and output positions completes the equipment and arrangements for making a frequency response test.

The input position is introduced in the continuously rotating armature of a synchro generator as shown in Fig. 23. If 110 volts is connected to the rotor of the generator, the input signal would represent a position error ranging over a 180 degree swing. The position error is made less by decreasing the rotor voltage. Since the output voltage from the rotor of a control transformer varies as a sinusoidal function of positional error between the control transformer and the synchro generator, the magnitude of the position error varies as a sinusoidal function of voltage in the continuously rotating generator. The magnitude of the position error can be found by

$$\theta = \sin^{-1} \frac{E}{E\ max} = \sin^{-1} \frac{E}{110}$$

The output position is represented by the oscillating movements of the synchro generator which is coupled to the repulsion motor of the servomechanism. To measure the magnitude of the oscillations a control transformer is connected to the generator as shown in Fig. 24. The control transformer rotor is blocked but is adjusted so that its output voltage is zero at the center or zero of each oscillation. The magnitude of the output is

$$\theta_{out} = \sin^{-1} \frac{E}{E_{max}}$$

The equipment and arrangements described previously will test the open loop frequency response of the servomechanism; however, when the test was placed in operation, it was found that the output position of the system tended to drift which would cause inaccuracy in the measurements. Although the test was designed for the open loop system, it was decided to introduce a very small feedback which would merely cancel the effect of drift in the open loop system. When the amount of feedback is determined, adjustments can be made in all the data so that the open loop test is not affected.

The equipment and arrangements for introducing the small feedback is shown in Fig. 25. A control transformer is connected to the servo output generator. The rotor of this control transformer is connected in series with the control transformer which provides the input error signal. the magnitude of the feedback is controlled by a variable autotransformer which is connected to the rotor of the output generator. A very small voltage in the generator produces a very small feedback voltage.

The maximum voltage from the control transformer is fifty five volts with maximum volts in the generator and ninety degrees difference in position of the rotors, it was found that three volts output from the control transformer was sufficient feedback to prevent drift.

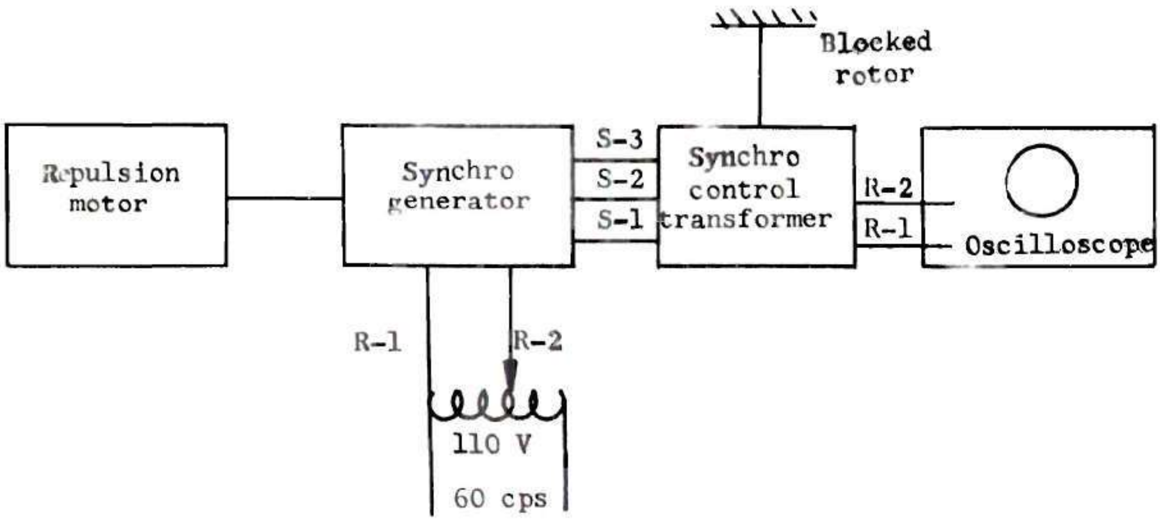


Fig. 24. Equipment Setup to Measure the Magnitude of the System Output.

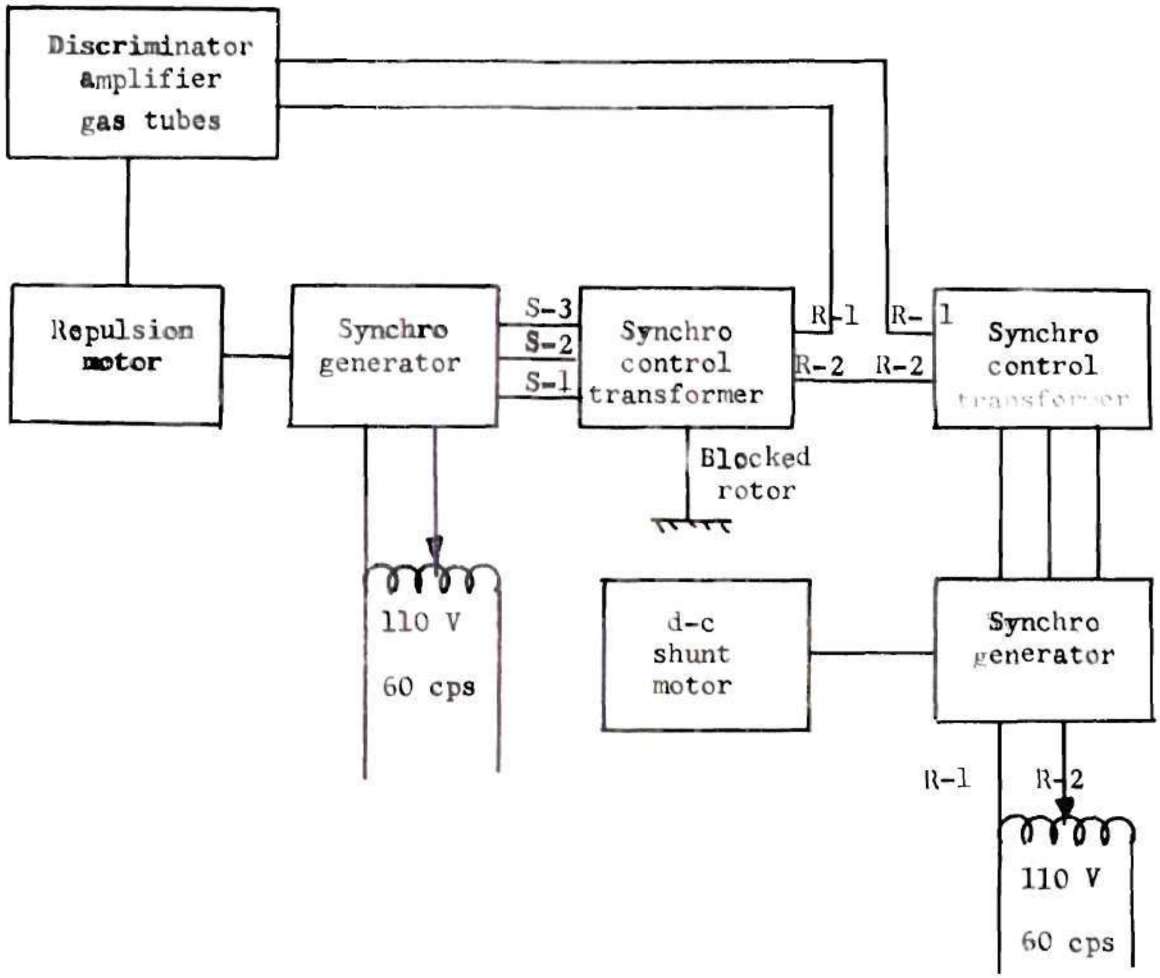


Fig. 25. Equipment Arrangements for Anti Drift Feedback.

The input error signal causes the system to oscillate. The feedback control transformer does not affect the oscillation, but it does decrease the magnitude of the oscillation. The magnitude of the feedback varies in a sinusoidal manner according to the maximum value of the oscillation. Hence, if the magnitude of the oscillation is θ_1, then the feedback voltage is

$$V = 3 \sin \theta_1$$

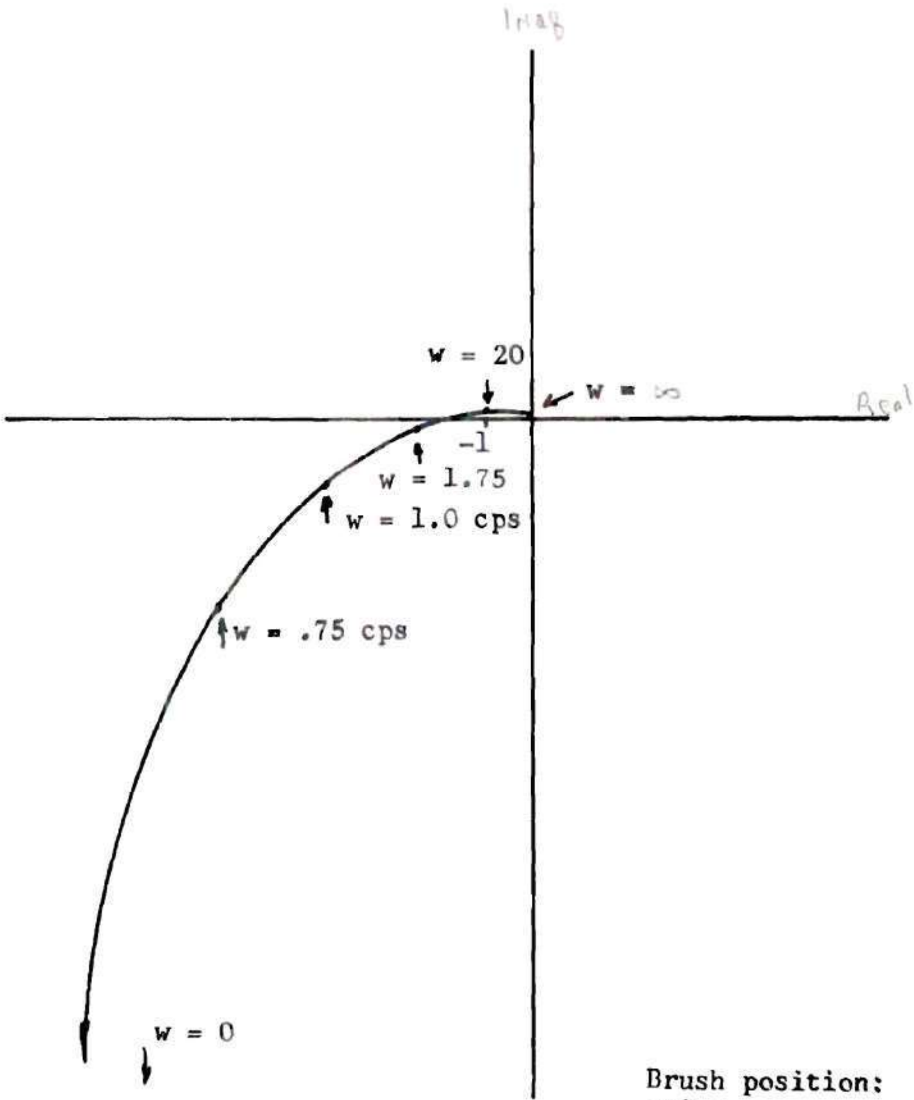
Three volts is the maximum amount of feedback used. Since fifty five volts would represent maximum feedback, the magnitude of the actual feedback is

$$\theta = \sin^{-1} \frac{V}{55} = \sin^{-1} \frac{3 \sin \theta_1}{55}$$

The magnitude of the oscillations are diminished by the above amount; therefore, the magnitude of the oscillations is adjusted by the addition of the feedback angle.

Discussion of results of the frequency response test.--The frequency response test was performed on the system with the brushes located 25 degrees from the neutral axis which is the maximum brush position. The results of the test is shown in Table 13 in the Appendix.

Fig. 26 shows a plot of the ratio of the output position to the input error signal in the complex plane. The magnitude of the ratio is approximately 2.0 where the curve crosses the negative real axis. The frequency of the error signal corresponding to this value of the ratio is ap--proximately two cycles per second. The value of the ratio apparently approaches zero at a phase angle of 90 degrees, and it approaches infinity



Brush position:
25^{o} from neutral axis

Fig. 26. Frequency Response—Output Position to Input Error Signal.

at a phase angle of 270 degrees. The frequency of the error signal approaches infinity for the former case and zero for the latter case. Actually, measurements could not be made on the system for error signal frequencies which were less than 0.5 cycles per second or greater than 3.0 cycles per second.

The general shape of the curve of Fig. 26 can be anticipated through consideration of the transfer function of the open loop system, and the general transfer function can be written from each of the time delays which is inherent in the system.

The general transfer function is

$$\frac{\theta_o}{E} = \frac{1}{jw\,(jwT_m + 1)(jwT_o + 1)}$$

where θ_o represents the output position, and E represents the input error signal. No time delay is expected in the error detector, but a filter condenser was installed across the output of the discriminator which introduces the time delay factor $(jwT_o + 1)$. No time delay is inherent in the amplifier or the gas tube switching devices. The time delay factor $(jwT_m + 1)$ results from inertia and friction within the motor. The factor jw is the natural time delay of the motor since the motor acts as an integrating device.

If the frequency of the error signal approaches zero, the value of the transfer function becomes

$$\frac{\theta_o}{E} = \infty \angle -90^\circ$$

If the frequency of the error signal approaches infinity, the value of the transfer function becomes

$$\frac{\theta_o}{E} = 0 \underline{/-270^\circ}$$

Equipment and arrangements for making velocity test.--Fig. 27 shows a schematic of the equipment arrangements which was used for the velocity test. In this test the feedback loop is closed, and a velocity input error signal is introduced into the system. That is the rotor of the input synchro control transformer is rotated at a constant angular velocity. Since the loop is closed, the rotor of the output synchro generator is forced by the system into a corresponding angular velocity to match that of the input. If the velocity limit of the repulsion motor is not exceeded, the steady state output angular velocity will equal the input angular velocity. However, there will be some angle which the rotor of the output generator will lag that of the input control transformer. The problem will be to find this error angle for any input velocity.

In Fig. 27 the rotor of the input control transformer is mechanically connected to a variable drive d-c motor, so that a fixed angular velocity can be introduced into the system. A second synchro (it makes no difference whether this unit is a generator or a control transformer) is mechanically coupled to the first. The stator of the second synchro can be rotated independently of the rotor. Two of the stator terminals of this second synchro were connected to the horizontal plates of an oscilloscope, while the same relative stator terminals of the output generator is connected to the vertical plates. The figure on the oscilloscope

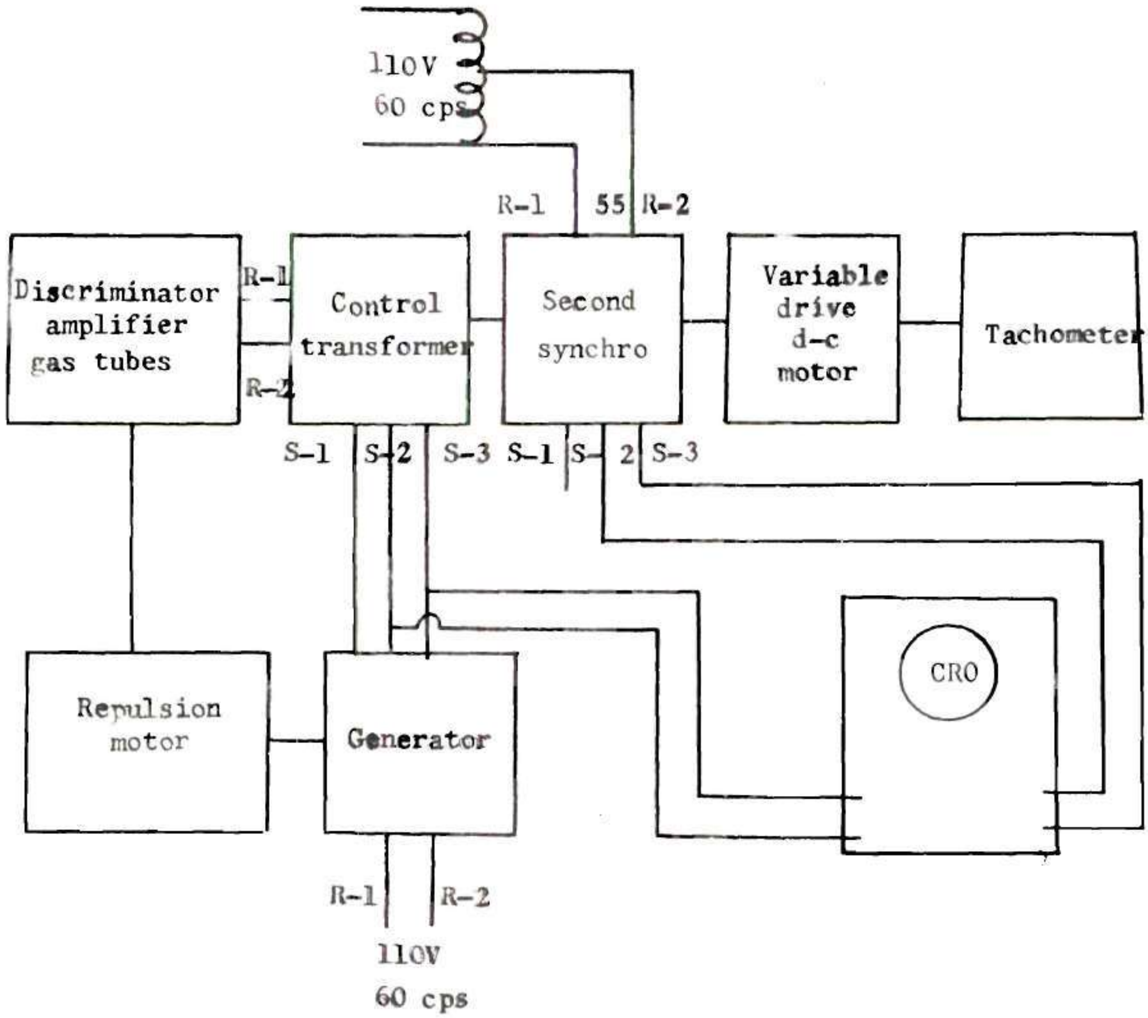


Fig. 27. Equipment Arrangements for Velocity Test.

indicates whether the generators are in phase. The type figures encountered on the screen has been discussed previously. If the rotors are not in phase, it is only necessary to turn the stator of the synchro until the figure on the screen indicates that the rotors are in phase. The phase difference is merely the number of degrees which the synchro stator turns to bring the signals in phase.

In this test a constant angular velocity is introduced into the system, and a phase angle difference or error between the input velocity and the output velocity is measured. Amounts of power absorbed by the motor for various degrees of speed was also noted.

Results of the velocity test.--In the test the rotor of the input control transformer was turned at various velocities, while the degrees of error in the input and output synchro rotors was measured. The amount of power delivered to the repulsion motor was also measured. These tests were performed with the brushes located in four different positions.

The curves shown in Fig. 28 are plotted for speed of the repulsion motor versus degrees error in the synchro rotors. Each of the four curves shown represents a different brush position. When the angle of the brushes from the neutral axis was 25 degrees (this position was the maximum possible brush shift), the synchro rotor error increased in a more linear manner for increase in motor speed than for lesser brush positions. The speed of the motor was greater for small angles of the brush positions while the degrees error was small. At 20 degrees of error the motor turned at 1200 revolutions per minute where the angle of the brushes was 10 degrees (this was the minimum possible position). For the same 20 degrees error and for a brush position of 25 degrees, the motor turned at 850 revolutions per minute. The top speed of the motor was approximately 2400 revolutions per

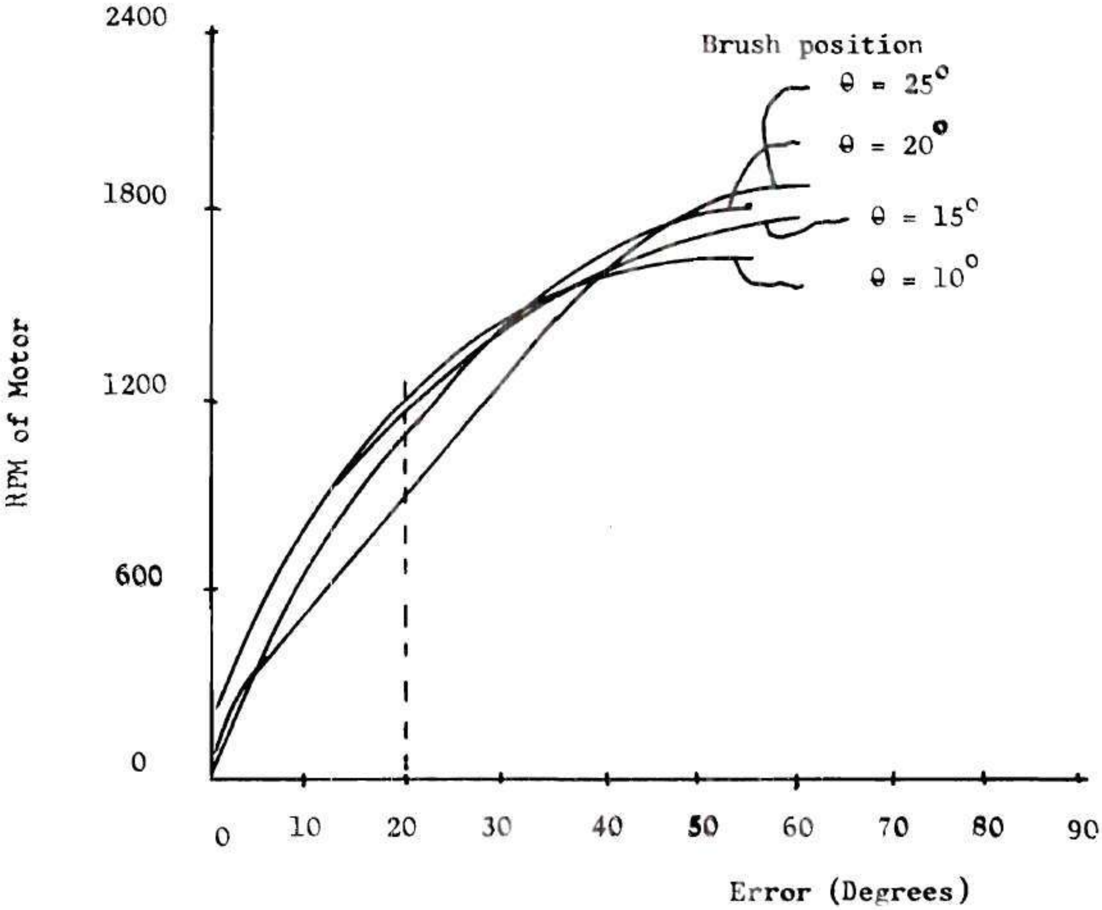


Fig. 28. Motor Speed Versus Degrees Error for Various Brush Positions.

minute. Measurements could not be made for degrees error greater than 60 degrees.

Fig. 29 shows curves representing motor speed versus power delivered to the motor for the various brush positions. The four curves are very similar. Less power is used by the motor for small angles of the brush position. Power also decreases very rapidly for an increase in motor speed.

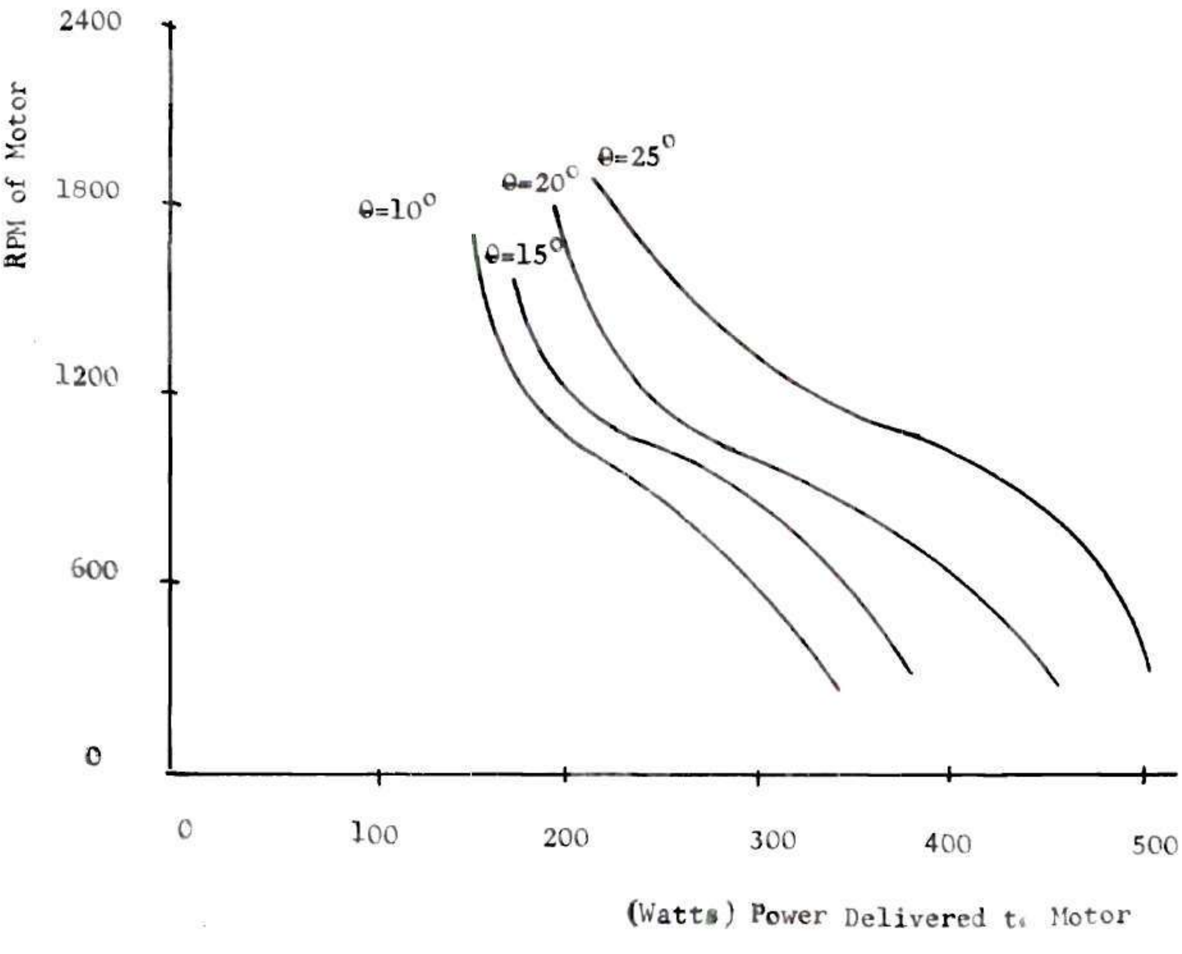


Fig. 29. Power Delivered to Motor Versus Motor Speed for Various Brush Positions.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The proposed servomechanism was constructed and tested. The motor of the system delivered a high starting torque which may be expected of a repulsion motor, and the system appeared to operate satisfactorily as a position servomechanism.

Performance of the system.--The magnitude of the starting torque for the proposed servomechanism is dependent on brush position. All positions of the brushes are not obtainable for the brush holder design which was used in this system. The greatest torque available in this system is obtained when the brushes are in their maximum position, i. e., when the angle between the neutral axis and the brushes is approximately 25 mechanical degrees. The greatest torque for the particular motor used in this system would occur when the angle of the brushes is approximately 30 mechanical degrees. The two sets of brushes can not be placed in that position at the same time. Less torque is developed, of course, when the angle of the brushes is decreased. Less torque is also developed should the angle of the brushes be increased beyond the point of maximum torque.

In Fig. 30 a plot is shown of rationalized starting torque versus degrees error in the error detector system. The position of the brushes is 25 degrees from the neutral axis. The maximum starting torque is about 425 ounce-inches.

The power absorbed by the motor while developing starting torque is also dependent on brush position. Small amounts of power are used when

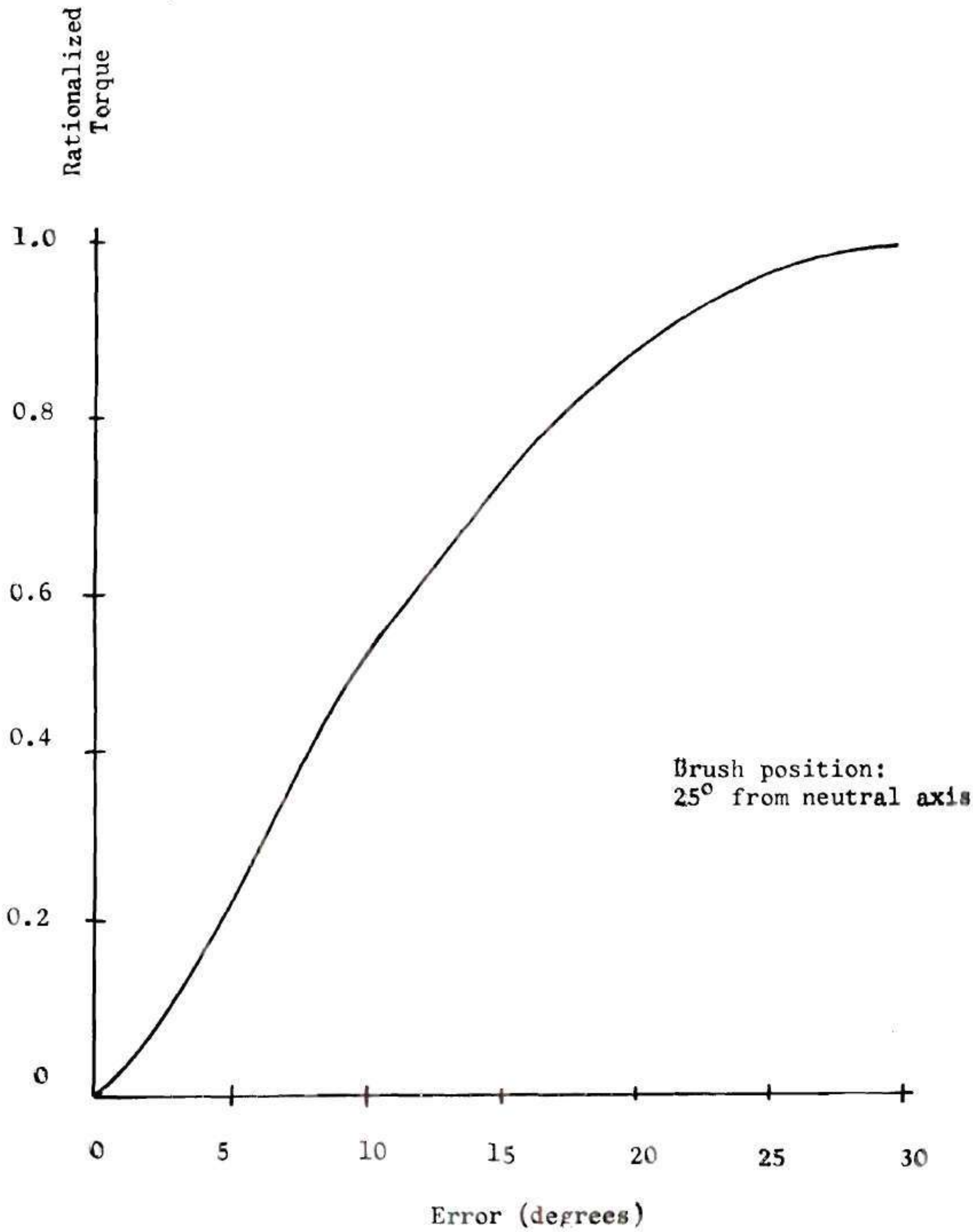


Fig. 30. Rationalized Starting Torque Versus Degrees Error.

the angle of the brushes is small. The power increases when the angle of the brushes is increased.

The amount of power absorbed by the motor is much larger when the motor is at rest than when it is running. When the motor is at rest there are eight brushes resting on the commutator. The width of a brush equals approximately the width of two and one half commutator segments. Thus, several commutator segments are shorted out by these brushes when the motor is at rest. When the motor is running, the effect of shorted commutator segments is decreased.

Total torque in the motor is developed for fewer degrees of the error signal for very small angles of the brushes than for larger brush angles. This feature results in greater instability of the system for small brush angles. Thus higher starting torque and better stability seem to go together when the angle of the brushes is increased (this would not be true if the brushes were advanced beyond the point of maximum torque).

In Fig. 31 the curve represents the open loop frequency response of the system with the brushes at 25 degrees from the neutral axis. The speed of the open loop frequency response is approximately 2.0 cycles per second with 180 degrees phase shift.

The curve shown in Fig. 32 is plotted for speed of the repulsion motor versus degrees error in the synchro rotors with the brush position at 25 degrees from the neutral axis. It can be seen that the curve is somewhat linear until synchronous speed of the motor is approached. The top speed of the motor is approximately 2400 revolutions per minute. The servomechanism does not operate satisfactorily at that speed.

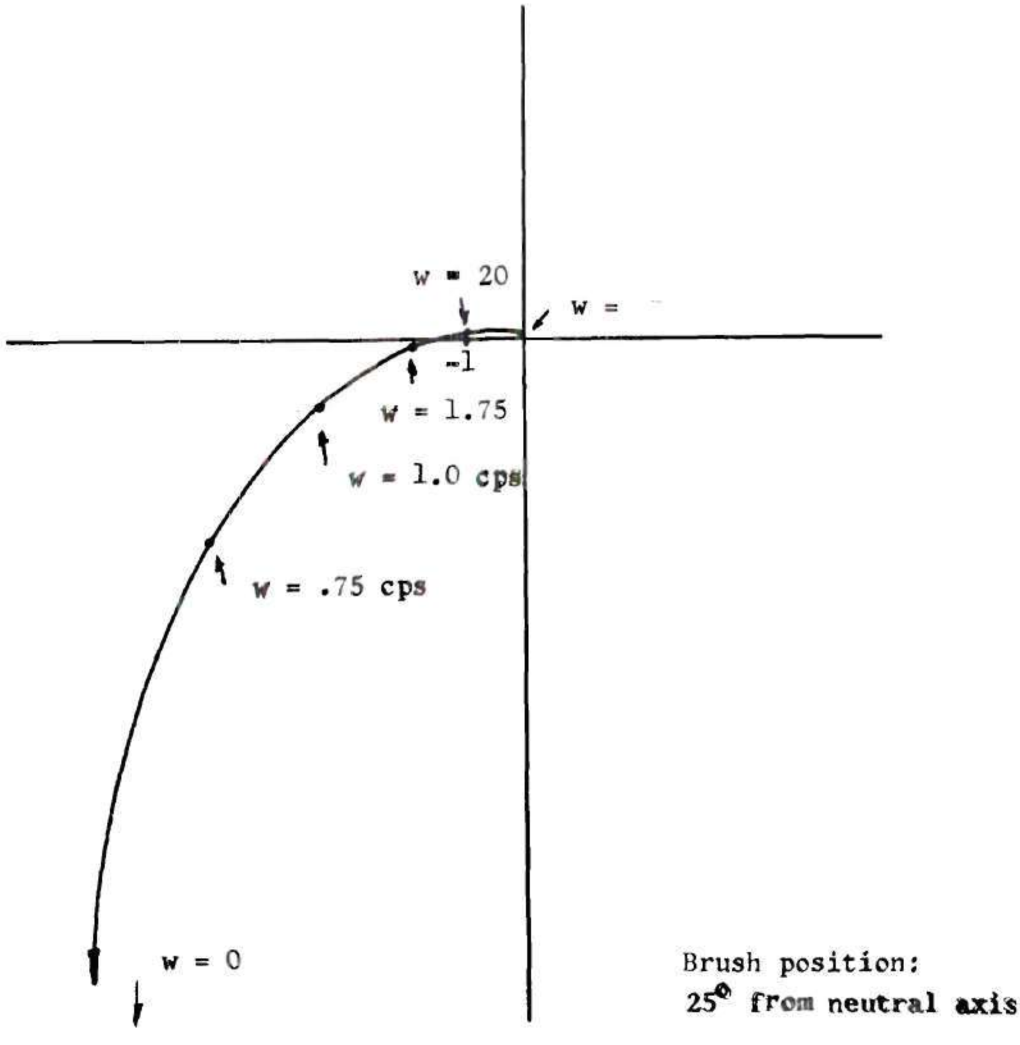


Fig. 31. Frequency Response-Output Position to Input Error Signal.

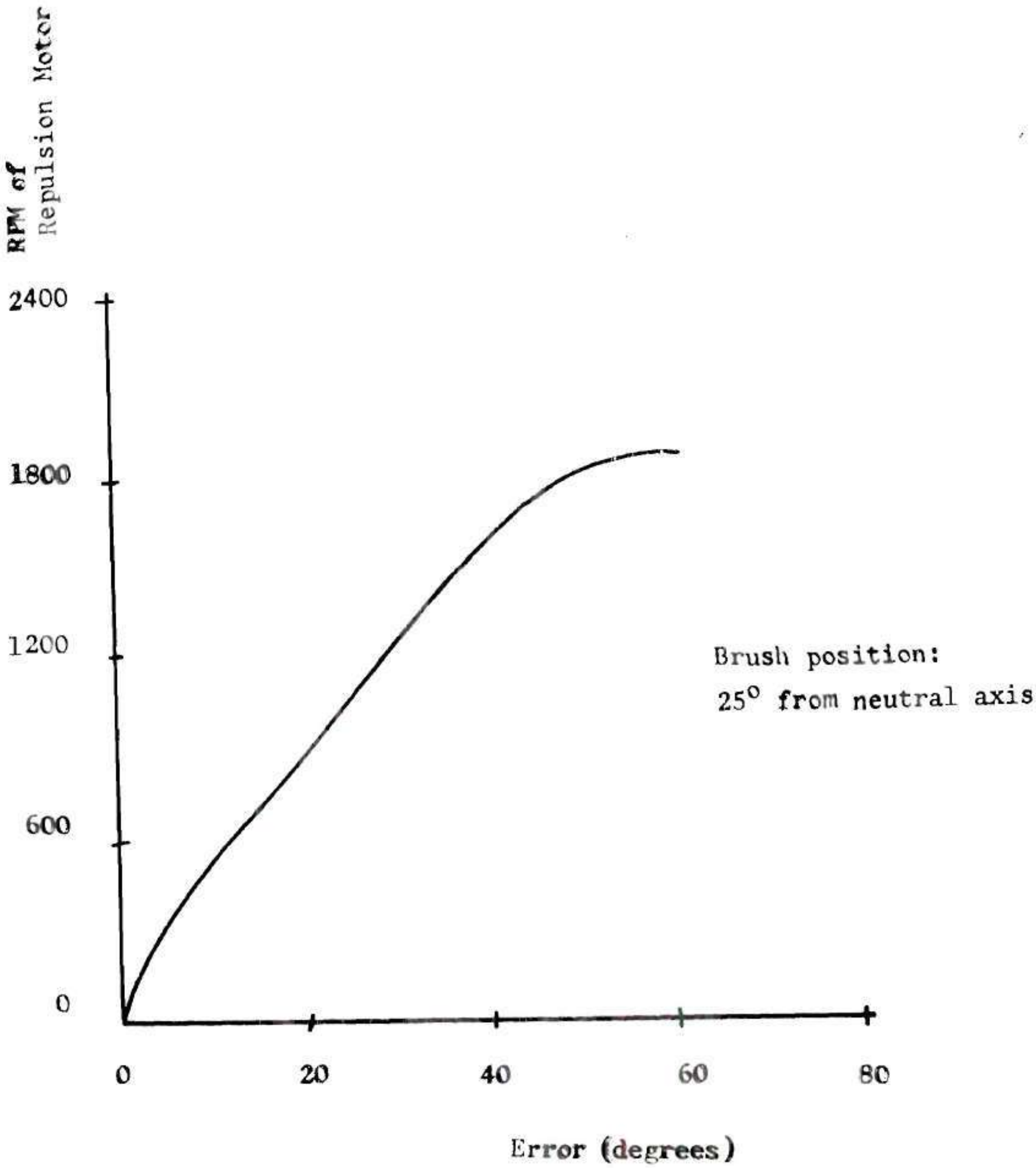


Fig. 32. Motor Speed Versus Degrees Error for the Closed Loop System.

Servomechanisms which use rotating amplifiers or magnetic amplifiers as their control elements have some built in time delays which are inherent in the controllers. The controller of the proposed servomechanism uses the principle of short circuiting brushes with grid controlled gas tubes which results in practically no time delay.

Recommendations:--Many possibilities exist for improving the proposed servomechanism. For instance, power is wasted in the system when the motor is at rest or is turning at a very slow velocity due to the short circuit that exist across adjacent commutator segments. The effect of this short circuit can possibly be decreased by increasing the length of the commutator and by decreasing the width of the brushes.

When a small error signal is introduced into the system, the gas tubes conduct only for a small portion of a cycle of the brush voltage. On the other hand, the brushes are applying a short circuit across adjacent commutator segments for the entire cycle. This feature results in a waste of power. A system could possibly be designed using gas tubes which would supply current to the system for less than a whole interval of a cycle when small error signals exists, thereby decreasing the effect of short circuited commutator segments.

APPENDICES

APPENDIX A

STARTING TORQUE DATA FOR A STRAIGHT REPULSION MOTOR

Tables 1 through 8 of this appendix show measurements of starting torque versus position error for eight different brush positions. This test was made with one set of brushes only in contact with the commutator so that the motor was simply a straight repulsion motor. Voltage, current and power measurements were recorded across both the brush circuit and the stator.

Table 1. Starting Torque versus Position Error for a Brush Position (for a Straight Repulsion Motor - One Set of Brushes Only)

(Degrees from Neutral Axis) Brush Position	(Oz.-Ins.) Torque	(Degrees) Position Error	Brush (Amps) Current	Brush Voltage	Brush (Watts) Power	Stator (Amps) Current	Stator Voltage	Stator (Watts) Power
45^{o}	0	0	7.0	43.0	75	7.0	110	210
	0	2.5	8.0	43.0	50	7.1	110	215
	0	5.0	13.2	42.5	85	8.8	110	285
	0	7.5	20.0	42.5	125	11.0	110	430
	0	10.0	24.0	41.0	162	12.5	110	600
	0	12.5	25.0	39.0	175	13.5	110	700
45^{o}	0	15.0	27.0	35.0	200	14.0	110	800
	0	17.5	31.0	31.0	250	16.0	110	1000
	0	20.0	32.5	27.5	255	16.5	110	1050
	0	22.5	33.0	23.5	275	16.5	110	1050
	0	25.0	33.0	13.0	275	16.5	110	1100
	0	27.5	33.0	7.5	275	16.5	110	1100
	0	30.0	33.0	7.5	275	16.5	110	1100
45^{o}	0	32.5	33.0	7.5	275	16.5	110	1100

Table 2. Starting Torque versus Position Error for a Brush Position (for a Straight Repulsion Motor - One Set of Brushes Only)

(Degrees from Neutral Axis) Brush Position	(Oz.-Ins.) Torque	(Degrees) Position Error	Brush (Amps) Current	Brush Voltage	Brush (Watts) Power	Stator (Amps) Current	Stator Voltage	Stator (Watts) Power
39.4°	7.2	0	6.5	43.0	75	7.1	110	215
	14.4	2.5	6.7	42.5	75	7.2	110	220
	21.6	5.0	12.1	41.8	95	8.9	110	290
	32.4	7.5	19.0	42.0	112	10.0	110	420
	39.6	10.0	22.3	41.0	115	11.0	110	480
	46.8	12.5	25.0	39.0	175	12.0	110	700
39.4°	82.8	15.0	29.0	34.0	200	12.0	110	800
	111.6	17.5	31.0	30.0	200	14.0	110	900
	151.2	20.0	31.5	27.0	225	14.0	110	950
	187.2	22.5	33.0	24.0	250	15.0	110	1050
	208.8	25.0	33.5	17.0	250	15.5	110	1100
	262.0	27.5	33.5	11.0	275	15.0	110	1100
	276.0	30.0	32.5	8.0	250	15.0	110	1050
39.4°	276.0	32.5	31.5	8.0	250	14.5	110	1050

Table 3. Starting Torque versus Position Error for a Brush Position (for a Straight Repulsion Motor - One Set of Brushes Only)

(Degrees from Neutral Axis) Brush Position	(Oz.-Ins.) Torque	(Degrees) Position Error	Brush (Amps) Current	Brush Voltage	Brush (Watts) Power	Stator (Amps) Current	Stator Voltage	Stator (Watts) Power
33.0°	65.0	0	6.7	41.0	75	6.4	110	220
	75.6	2.5	7.0	40.0	80	6.5	110	220
	100.8	5.0	10.2	39.5	85	7.4	110	270
	118.8	7.5	15.2	40.0	90	9.5	110	390
	147.6	10.0	19.5	40.0	112	11.0	110	515
	363.6	12.5	23.1	38.5	150	11.0	110	675
33.0°	399.6	15.0	22.0	34.0	138	11.0	110	675
	422.2	17.5	23.5	30.0	150	11.5	110	750
	432.0	20.0	24.1	25.0	160	11.0	110	800
	450.0	22.5	26.0	21.0	175	13.5	110	850
	507.6	25.0	27.0	12.0	200	14.0	110	875
	540.0	27.5	27.5	7.5	200	14.0	110	875
	565.0	30.0	26.0	6.5	200	14.0	110	1000
33.0°	565.0	32.2	27.0	6.5	200	14.0	110	1000

Table 4. Starting Torque versus Position Error for a Brush Position (for a Straight Repulsion Motor - One Set of Brushes Only)

(Degrees from Neutral Axis) Brush Position	(Oz.-Ins.) Torque	(Degrees) Position Error	Brush			Stator		
			(Amps) Current	Voltage	(Watts) Power	(Amps) Current	Voltage	(Watts) Power
26.6°	29.0	0	6.5	39.5	50	6.0	110	220
	36.0	2.5	7.5	40.0	60	6.0	110	240
	144.0	5.0	10.0	39.0	60	6.5	110	270
	254.0	7.5	11.0	37.0	65	7.5	110	320
	252.0	10.0	12.5	36.0	70	8.5	110	390
	292.0	12.5	15.0	33.0	70	8.8	110	450
26.6°	378.0	15.0	16.2	31.0	75	9.0	110	510
	406.0	17.5	17.0	27.5	80	9.5	110	540
	450.0	20.0	18.5	23.0	100	10.0	110	620
	467.0	22.5	19.0	19.0	110	10.4	110	640
	558.0	25.0	19.5	15.0	110	10.4	110	670
	468.0	27.5	19.0	7.5	100	10.0	110	600
	468.0	30.0	16.5	5.0	75	10.0	110	640
26.6°	468.0	32.5	16.5	5.0	75	10.0	110	640

Table 5. Starting Torque versus Position Error for a Brush Position (for a Straight Repulsion Motor - One Set of Brushes Only)

(Degrees from Neutral Axis) Brush Position	(Oz.-Ins.) Torque	(Degrees) Position Error	Brush (Amps) Current	Brush Voltage	Brush (Watts) Power	Stator (Amps) Current	Stator Voltage	Stator (Watts) Power
20.2°	54.0	0	3.8	31.0	37	5.2	110	220
	61.0	2.5	3.7	31.0	37	5.2	110	230
	90.0	5.0	4.7	29.7	30	5.4	110	242
	129.0	7.5	6.6	32.0	25	6.7	110	280
	183.0	10.0	7.5	30.0	28	6.5	110	310
	205.0	12.5	8.7	29.5	35	6.8	110	340
20.2°	224.0	15.0	9.7	27.0	40	7.5	110	420
	234.0	17.5	11.0	25.0	58	8.5	110	550
	320.0	20.0	12.6	19.0	65	9.6	110	570
	339.0	22.5	13.0	14.0	65	9.8	110	570
	346.0	25.0	13.2	7.5	65	9.8	110	580
	348.0	27.5	12.7	5.0	60	9.7	110	580
	348.0	30.0	12.5	4.0	60	9.6	110	570
20.2°	348.0	32.5	12.0	4.0	60	9.3	110	560

Table 6. Starting Torque versus Position Error for a Brush Position (for a Straight Repulsion Motor - One Set of Brushes Only)

(Degrees from Neutral Axis) Brush Position	(Oz.-Ins.) Torque	(Degrees) Position Error	Brush			Stator		
			(Amps) Current	Voltage	(Watts) Power	(Amps) Current	Voltage	(Watts) Power
13.8°	50.4	0	1.8	22.5	20	3.8	110	130
	50.0	2.5	2.0	22.0	18	3.9	110	130
	72.0	5.0	2.9	24.0	20	4.4	110	180
	90.0	7.5	3.3	25.0	15	4.7	110	200
	97.0	10.0	4.6	25.0	18	5.0	110	240
	108.0	12.5	6.2	24.0	22	5.4	110	290
13.8°	126.0	15.0	6.9	21.0	22	6.5	110	400
	133.0	17.5	7.0	20.0	23	6.8	110	410
	162.0	20.0	6.5	15.0	15	7.2	110	220
	155.0	22.5	5.5	11.0	15	4.7	110	210
	162.0	25.0	5.7	4.5	15	4.9	110	190
	162.0	27.5	5.3	3.0	12	4.7	110	175
	162.0	30.0	5.3	3.0	12	4.7	110	175
13.8°	162.0	32.5	5.3	3.0	12	4.7	110	175

Table 7. Starting Torque versus Position Error for a Brush Position (for a Straight Repulsion Motor - One Set of Brushes Only).

(Degrees from Neutral Axis) Brush Position	(Oz.-Ins.) Torque	(Degrees) Position Error	Brush (Amps) Current	Brush Voltage	Brush (Watts) Power	Stator (Amps) Current	Stator Voltage	Stator (Watts) Power
6.4^{o}	36.0	0	1.3	17.0	10	4.6	110	210
	42.0	2.5	1.3	16.5	10	4.6	110	210
	68.0	5.0	1.7	15.0	9	4.7	110	210
	90.0	7.5	2.2	13.0	8	4.8	110	215
	97.0	10.0	2.5	11.0	7	4.8	110	220
	104.0	12.5	2.8	8.0	7	4.8	110	220
6.4^{o}	108.0	15.0	2.9	6.0	6	4.8	110	220
	108.0	17.5	3.0	4.0	6	4.8	110	225
	108.0	20.0	3.0	3.0	6	4.8	110	225
	108.0	22.5	2.9	2.0	7	4.8	110	225
	108.0	25.0	2.9	2.0	7	4.8	110	225
	108.0	27.5	3.0	1.5	7	4.8	110	225
	108.0	30.0	2.7	2.0	5	4.8	110	225
6.4^{o}	108.0	32.5	3.0	1.5	5	4.8	110	225

Table 8. Starting Torque versus Position Error for a Brush Position (for a Straight Repulsion Motor - One Set of Brushes Only).

(Degrees from Neutral Axis) Brush Position	(Oz.-Ins.) Torque	(Degrees) Position Error	Brush (Amps) Current	Brush Voltage	Brush (Watts) Power	Stator (Amps) Current	Stator Voltage	Stator (Watts) Power
0°	0	0	0	0	0	8.3	110	440
	0	2.5	0	0	0	8.3	110	440
	0	5.0	0	0	0	8.3	110	440
	0	7.5	0	0	0	8.3	110	440
	0	10.0	0	0	0	8.3	110	440
	0	12.5	0	0	0	8.3	110	440
0°	0	15.0	0	0	0	8.3	110	440
	0	17.5	0	0	0	8.3	110	440
	0	20.0	0	0	0	8.3	110	440
	0	22.5	0	0	0	8.3	110	440
	0	25.0	0	0	0	8.3	110	440
	0	27.5	0	0	0	8.3	110	440
	0	30.0	0	0	0	8.3	110	440
0°	0	32.5	0	0	0	8.3	110	440

APPENDIX B

STARTING TORQUE DATA FOR A MODIFIED REPULSION MOTOR

Tables 9 through 12 of this appendix show measurements of starting torque versus position error for four different brush positions. Both sets of brushes made contact with the commutator so that the motor would operate properly in the servomechanism. Voltage, current, and power measurements were recorded across both the brush circuit and the stator.

Table 9. Starting Torque versus Position Error for a Brush Position (for a Modified Repulsion Motor - Two Sets of Brushes)

(Degrees from Neutral Axis) Brush Position	(Oz.-Ins.) Torque	(Degrees) Position Error	Brush (Amps) Current	Brush Voltage	Brush (Watts) Power	Stator (Amps) Current	Stator Voltage	Stator (Watts) Power
25°	0	0	5.4	37.0	35	11.0	110	500
	36	2.5	7.0	35.0	35	10.0	110	500
	108	5.0	9.3	35.0	37	10.0	110	500
	124	7.5	10.0	34.0	40	11.0	110	550
	180	10.0	12.0	33.0	70	11.5	110	600
	198	12.5	15.0	32.5	80	12.0	110	650
	234	15.0	17.0	30.0	90	12.0	110	700
25°	238	17.5	18.2	26.0	100	12.5	110	750
	342	20.0	19.5	22.0	110	13.0	110	800
	364	22.5	19.7	17.0	115	13.1	110	825
	396	25.0	20.0	12.0	120	13.2	110	850
	406	27.5	20.0	9.0	125	13.4	110	850
	411	30.0	20.0	6.0	130	13.5	110	850
25°	422	32.5	20.0	6.0	130	13.5	110	850

Table 10. Starting Torque versus Position Error for a Brush Position (for a Modified Repulsion Motor - Two Sets of Brushes)

(Degrees from Neutral Axis) Brush Position	(Oz.-Ins.) Torque	(Degrees) Position Error	Brush (Amps) Current	Brush Voltage	Brush (Watts) Power	Stator (Amps) Current	Stator Voltage	Stator (Watts) Power
20°	0	0.0	4.5	30.0	30.0	8.5	110	430
	27	2.5	6.5	30.0	30.0	8.5	110	440
	54	5.0	8.5	30.0	30.0	8.5	110	450
	100	7.5	9.2	28.8	40.0	10.0	110	550
	151	10.0	10.0	27.5	50.0	11.5	110	650
	183	12.5	10.5	25.2	55.0	11.5	110	700
20°	216	15.0	11.0	23.0	60.0	11.5	110	700
	288	17.5	11.0	19.5	65.0	11.7	110	700
	340	20.0	11.0	16.0	70.0	11.8	110	700
	340	22.5	11.4	11.5	72.0	11.9	110	700
	340	25.0	11.8	7.0	75.0	12.0	110	700
	345	27.5	11.9	5.5	77.5	12.0	110	700
	350	30.0	12.0	4.0	80.0	12.0	110	700
20°	350	32.5	12.0	4.0	80.0	12.0	110	700

Table 11. Starting Torque versus Position Error for a Brush Position (for a Modified Repulsion Motor - Two Sets of Brushes)

(Degrees from Neutral Axis) Brush Position	(Oz.-Ins.) Torque	(Degrees) Position Error	Brush			Stator		
			(Amps) Current	Voltage	(Watts) Power	(Amps) Current	Voltage	(Watts) Power
15°	0	0.0	4.2	23.0	25	8.9	110	550
	0	2.5	5.3	25.0	27	8.9	110	560
	0	5.0	6.5	27.0	30	9.0	110	570
	65	7.5	8.5	25.0	32	9.5	110	605
	121	10.0	10.0	23.0	35	10.0	110	640
	160	12.5	11.7	22.0	40	10.2	110	640
15°	206	15.0	11.5	21.0	45	10.5	110	640
	218	17.5	12.0	17.0	47	10.5	110	670
	230	20.0	12.5	13.0	50	10.5	110	700
	236	22.0	12.2	9.0	50	10.5	110	685
	241	25.0	12.0	5.0	50	10.6	110	675
	245	27.0	11.7	4.0	50	10.6	110	670
	249	30.0	11.7	4.0	50	10.6	110	670
15°	249	32.0	11.7	4.0	50	10.6	110	670

Table 12. Starting Torque versus Position Error for a Brush Position (for a Modified Repulsion Motor - Two Sets of Brushes)

(Degrees from Neutral Axis) Brush Position	(Oz.-Ins.) Torque	(Degrees) Position Error	Brush (Amps) Current	Brush Voltage	Brush (Watts) Power	Stator (Amps) Current	Stator Voltage	Stator (Watts) Power
10°	0	0.0	3.3	17.0	12	9.0	110	390
	30	2.5	4.3	18.0	12	8.0	110	390
	61	5.0	5.2	20.0	12	7.0	110	390
	72	7.5	6.1	19.0	13	7.5	110	425
	83	10.0	7.1	18.0	15	8.0	110	450
	110	12.5	7.7	15.0	17	8.1	110	470
10°	141	15.0	8.5	12.0	18	8.3	110	490
	144	17.5	8.5	10.0	19	8.5	110	520
	147	20.0	8.4	8.0	20	8.8	110	550
	147	22.5	8.5	6.0	21	8.9	110	570
	147	25.0	8.7	4.0	22	9.1	110	590
	147	27.5	8.7	3.0	22	9.3	110	620
	147	30.0	8.7	3.0	22	9.5	110	640
10°	147	32.0	8.7	3.0	22	9.5	110	640

APPENDIX C

OPEN LOOP FREQUENCY RESPONSE

Table 13 of this appendix shows measurements of the open loop frequency response for the proposed servomechanism. Measurements were made for four different brush positions. The magnitude and frequency of the input and output positions were measured. A feedback just large enough to cause the output to center about a certain point was introduced. The magnitude of this feedback angle was added to the magnitude of the output position so that the open loop response would be unaffected.

Table 13. Open Loop Frequency Response for One Brush Position.

(Degrees from Neutral Axis) Brush Position	(CPS) Frequency of Input Error Signal	(Degrees) Magnitude of Input Error Signal	(Degrees) Uncorrected Magnitude of Output Position	(Degrees) Angle of Feedback	(Degrees) Corrected Magnitude of Output Position	(Degrees) Phase Shaft
25°	0.50	8.4	86.8	3.2	90.0	210
	0.75	9.0	86.8	3.2	90.0	205
	1.00	16.0	86.8	3.2	90.0	198
	1.25	16.0	59.0	2.0	61.0	190
	1.50	16.0	32.5	1.0	33.5	183
25°	1.75	18.0	26.0	1.0	27.0	179
	2.00	20.5	19.5	1.0	20.5	176
	2.25	22.0	18.0	1.0	19.0	169
	2.50	23.6	16.5	1.0	17.5	161
	3.75	18.0	13.0	1.0	14.0	151
25°	3.00	14.5	10.5	1.0	11.5	142

APPENDIX D

CLOSED LOOP VELOCITY TEST

Tables 14 through 17 show data of the velocity test. The feedback loop of the system was closed, and a velocity input signal was introduced. The angular difference between the synchro generator and control transformer rotors was measured for each velocity input. Amounts of power delivered to the motor was also recorded. The tests were made for four different brush positions.

Table 14. Closed Loop Velocity Test for Certain Brush Positions.

Brush Position: 25 Degrees from Neutral Axis.

(Cycles Per Second) Frequency of Input Signal	(Degrees) Position Error of Generator-Transformer	(Watts) Power to Motor Stator
0.50	3	510
1.00	12	490
1.50	20	440
2.00	29	330
3.00	50	230

Table 15. Closed Loop Velocity Test for Certain Brush Positions.

Brush Position: 20 Degrees from Neutral Axis.

(Cycles per Second) Frequency of Input Signal	(Degrees) Position Error of Generator-Transformer	(Watts) Power to Motor Stator
0.5	4	460
1.0	8	410
1.5	17	340
2.0	24	330
2.5	33	210
3.0	57	200

Table 16. Closed Loop Velocity Test for Certain Brush Position.

Brush Position: 15 Degrees from Neutral Axis.

(Cycles Per Second) Frequency of Input Signal	(Degrees) Position Error of Generator-Transformer	(Watts) Power to Motor Stator
0.5	2	390
1.0	11	350
1.5	14	300
2.0	18	250
2.5	35	180
3.0	61	195

Table 17. Closed Loop Velocity Test for Certain Brush Position.

Brush Position: 10 Degrees from Neutral Axis.

(Cycles Per Second) Frequency of Input Signal	(Degrees) Position Error of Generator-Transformer	(Watts) Power to Motor Stator
0.5	0	350
1.0	6	290
1.5	13	250
2.0	20	200
2.5	35	165

APPENDIX E

THEORY OF COMPONENTS

Repulsion motor.--Fig. 33 shows a diagrammatical representation of a repulsion motor. The motor consists of a stator winding connected directly across an alternating current power source, and a commutator armature with one pair of brushes per pair of poles. The brushes are located in a position off the neutral axis. The brushes are simply short circuited, and there is no external connection with the alternating current supply source except for the magnetic connection with the stator winding.

When the motor is considered at rest, and the stator connected to an alternating current supply, a current is induced in the rotor, the circuit being completed by the short circuited brushes. The rotor will start turning in the direction shown because of the torque resulting from the mutual action of the field and armature currents.

If the brushes lie on the neutral line, the mutual induction coefficient between the field and armature is equal to zero; therefore, no current will be induced in the armature by the alternating current flowing through the stator, and the torque will be equal to zero. If the brushes coincide with the poles, the mutual induction coefficient is at a maximum, and the alternating current flowing through the stator will induce a current in the armature which acts as the secondary shortcircuited winding of a transformer. No torque will be developed in this case because the direction of the magnetic flux produced by the current induced in the rotor is coincident with the flux produced by the current

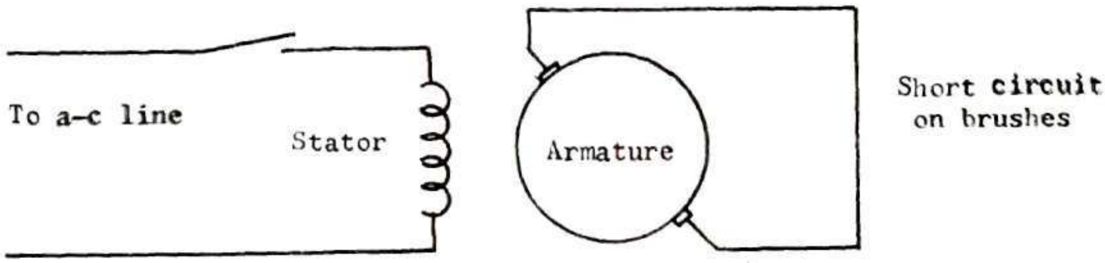


Fig. 33. Diagram of a Repulsion Motor.

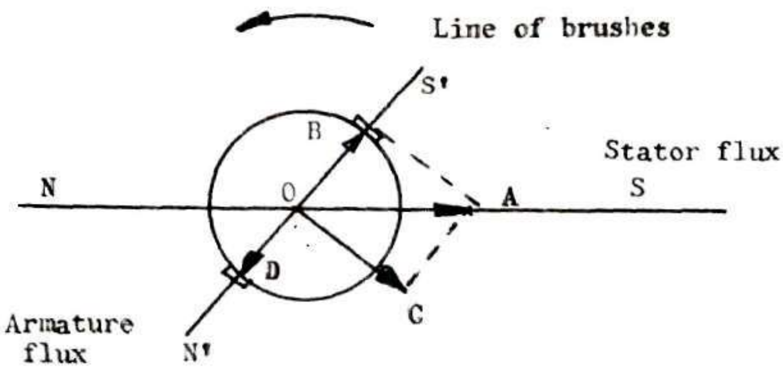


Fig. 34. Components of Stator Flux.

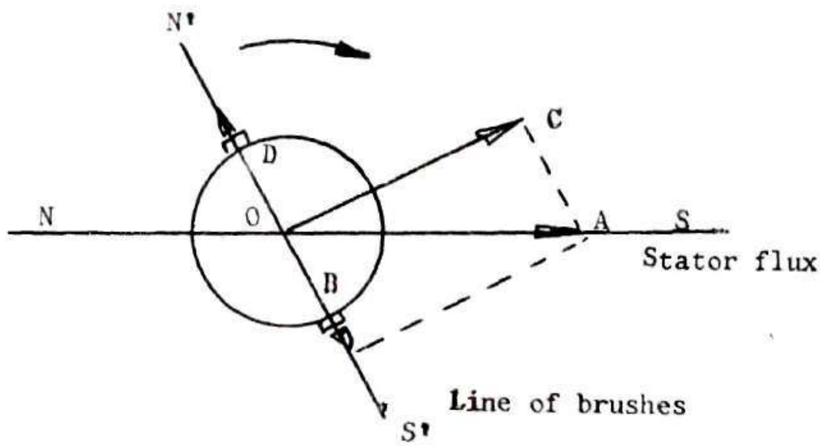


Fig. 35. Components of Stator Flux.

in the stator.

If the brushes lie between the neutral axis and the poles, a torque will arise. It can be shown that the rotor will rotate in the opposite direction to that in which the line of brushes lies with regard to the zero-torque line. In Fig. 34, let OA represent the stator flux at a given instant t. This flux can be split up into two components, the first being OB, in line with the brushes and the second OC, which is perpendicular to that line. The armature flux tends to annul the stator flux and will therefore lie along OD.

The result is that (for one-half of a cycle) the armature has a north pole N' and a south pole S' while the stator has a north pole N and south pole S as shown in figure. There will be repulsion between N and N' and between S and S', thus rotation will occur as shown. (1)*

Through the same line of reasoning, it can be shown that the armature will rotate in the reverse direction if the brushes are moved passed the line of the poles into the second and fourth quadrants of the plane of the poles and neutral axis. This situation is shown in Fig. 35. As in the preceding case, let OA represent the stator flux at any instant t. This flux can be resolved into two components, the first being OB in line with the brushes and the second being OC which is perpendicular to that line. The short circuited armature produces a flux which is in a direction that will tend to annul the stator flux. This flux is represented by the vector OD. Again the apparent result (for one half of a cycle) is that the armature has a north pole N' and a south pole S' while the stator has a north pole N and a south pole S as shown in the figure. There will be repulsion between N and N' and between S and S'; thus, rotation will occur in the indicated direction.

When the motor is running, there is a generated voltage in the armature. This voltage is a maximum along the neutral axis where the

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*Numbers in parentheses refer to the bibliography.

voltage due to transformer action is zero. The generated voltage is zero along the axis of the poles where the transformer action voltage is a maximum. Thus if the brushes are moved from the line of the poles to the neutral axis, the generated voltage will vary from zero to a maximum value while the transformer action voltage will vary from a maximum value to zero. These two types of voltages, where they exist, will have the same frequency as that of the alternating current supply. Like the transformer voltage, the generated voltage is short circuited by the brushes. Generated currents produce retarding torque, thus a dampening torque exists in a repulsion motor.

Gas tubes.--In the proposed servomechanism, grid controlled gas tubes (thyratrons) are used for the control of the power. The grid controlled gas tube is one in which the control electrode is installed between the cathode and the plate. This grid or control electrode serves a function which is analygous to that of the control grid of an ordinary vacuum tube.

In an ordinary vacuum tube, the control grid can start the flow of current in the tube, regulate the amount of current flowing, and it can also force a stop to the flow of current. However, the grid of the gas tube is able only to initiate the flow current, and, once the current flows, the grid has no further influence over the flow of current. This grid can not stop the flow of current. The current can be stopped only by making the plate potential zero or negative for a short period of time.

> The relations between the grid and plate potential at the moment of the initiation of the arc are similar to those which apply at cut-off in vacuum triode. As the plate potential is made less positive, the grid potential must be made relatively more positive to start the arc. The starting voltage characteristic of a typical thyratron is shown in Fig. 6. Over a large part of the characteristic, it is seen that the ratio of positive plate potential to negative grid potential is nearly constant. This ratio is known as the "control ratio" . . (2)

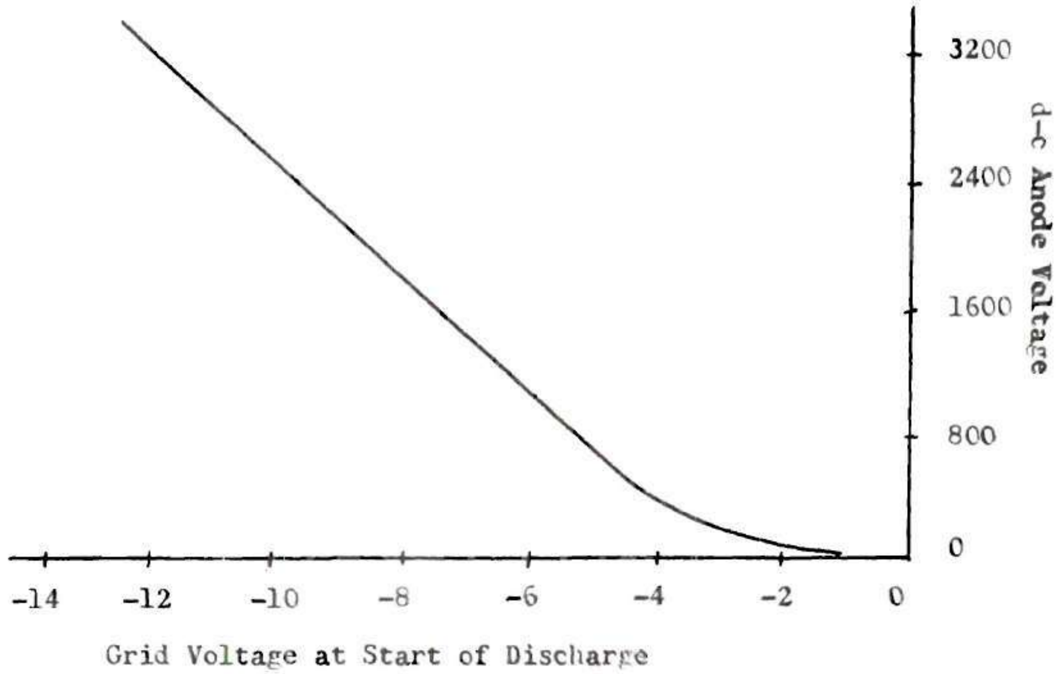

Fig. 36. Starting Characteristics of a Thyratron Using Mercury.

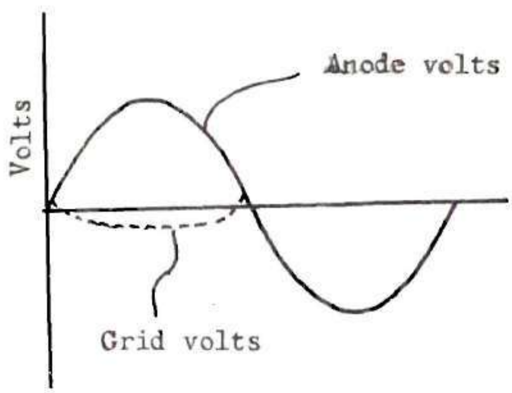

Fig. 37. Critical Grid Voltage Versus Anode Voltage for a Typical Thyratron.

When an a-c voltage is applied to the plate of a thyratron, the current flow is cut off during each negative half cycle. By the application of the proper grid voltage at the proper time, the current flow may be initiated at any time during a positive half cycle. The critical grid voltage, which is that value of grid voltage necessary to start the flow of current, is a function of anode voltage and of tube temperature. A curve showing anode voltage versus critical grid voltage for an alternating voltage is shown in Fig. 36.

This curve showing anode voltage versus critical grid voltage can be obtained by point by point plotting from a starting characteristics curve such as shown in Fig. 37. Any time, during a positive half cycle, that the value of the grid voltage equals the critical grid voltage, current will be initiated and will continue to flow for the remainder of the cycle.

A convenient method of controlling the point of intersection of the grid voltage and the critical grid voltage curve is called bias-shift control. This method can be used when an a-c voltage is applied to the anode.

Bias shift control makes use of a variable d-c supply and a large alternating voltage whose phase is lagging that of the anode voltage by a fixed amount. The variable d-c voltage is connected in series with the grid alternating voltage so that the axis of the latter voltage can be shifted up or down with respect to the critical grid voltage curve.

Fig. 38 shows the situation when the variable d-c voltage is zero. The phase of the alternating grid voltage is lagging the anode voltage by 90 degrees. If the critical grid voltage is assumed to be zero, the

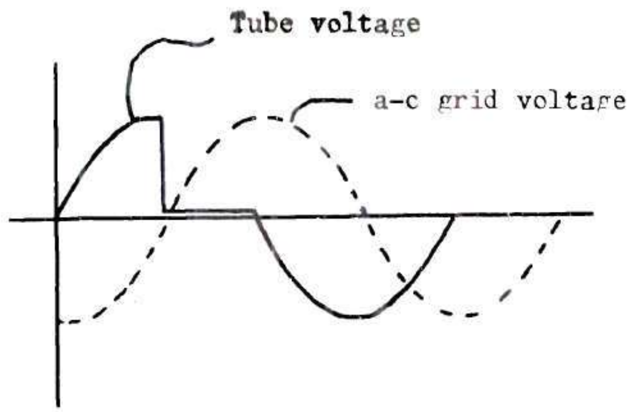

Fig. 38. Tube Voltage Waveform Using Bias-phase Control with Zero d-c bias.

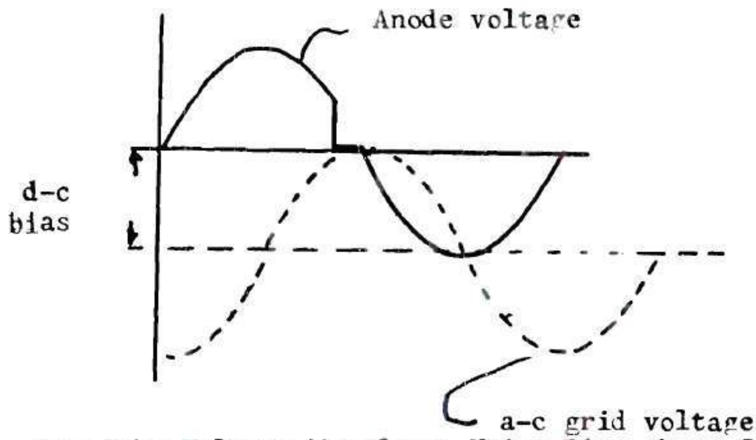

Fig. 39. Gas Tube Voltage Waveforms Using Bias-phase Control with a Negative d-c Bias in Series with a-c Grid Voltage.

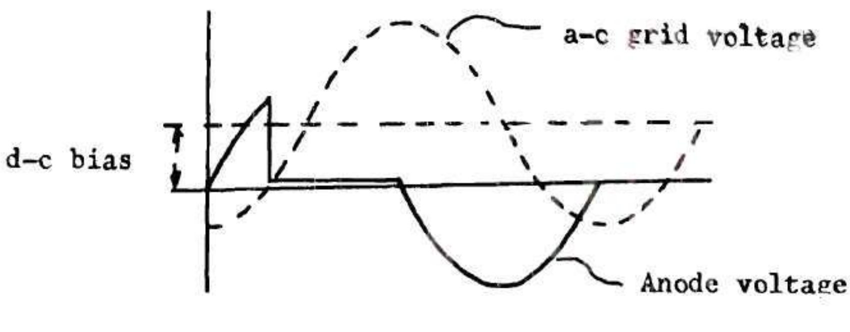

Fig. 40. Gas Tube Voltage Waveforms Using Bias-phase Control with a Positive d-c Bias in Series with the a-c Grid Voltage.

angle of firing is approximately ninety degrees. The tube is firing during fifty per cent of the positive cycle.

In Fig. 39 the variable d-c voltage is made negative. The alternating grid voltage wave has been shifted down, and the point of intersection of this wave with the critical grid voltage line has been shifted to the right. Therefore, the angle of firing is approximately 135 degrees. If the d-c voltage is made even more negative, the grid a-c voltage shifts further down, the point of intersection shifts to the right, and the tube is more nearly cut off. The tube is completely cut off when the value of the d-c voltage exceeds the peak value of the a-c grid voltage.

In Fig. 40 the variable d-c voltage is made positive. The a-c grid voltage is shifted up, and the tube fires over a large portion of the positive cycle. The tube fires all during the positive cycle when the value of the d-c voltage exceeds the peak value of the a-c grid voltage.

Error detector.--The error detector system used in the proposed servomechanism consists of the synchro generator and control transformer.

The structure of the generator and control transformer is similar to that of a small three phase alternator. The rotor has a single winding which is terminated in slip rings. The stator has three windings which are spatially displaced 120 degrees from each other. Usually the stator or the rotor laminations are skewed on slot pitch to eliminate slot lock and the resulting angular errors.

The operation of the generator and control transformer may be seen by an analysis of an ideal system as shown in Fig. 41. Let E_1 be the

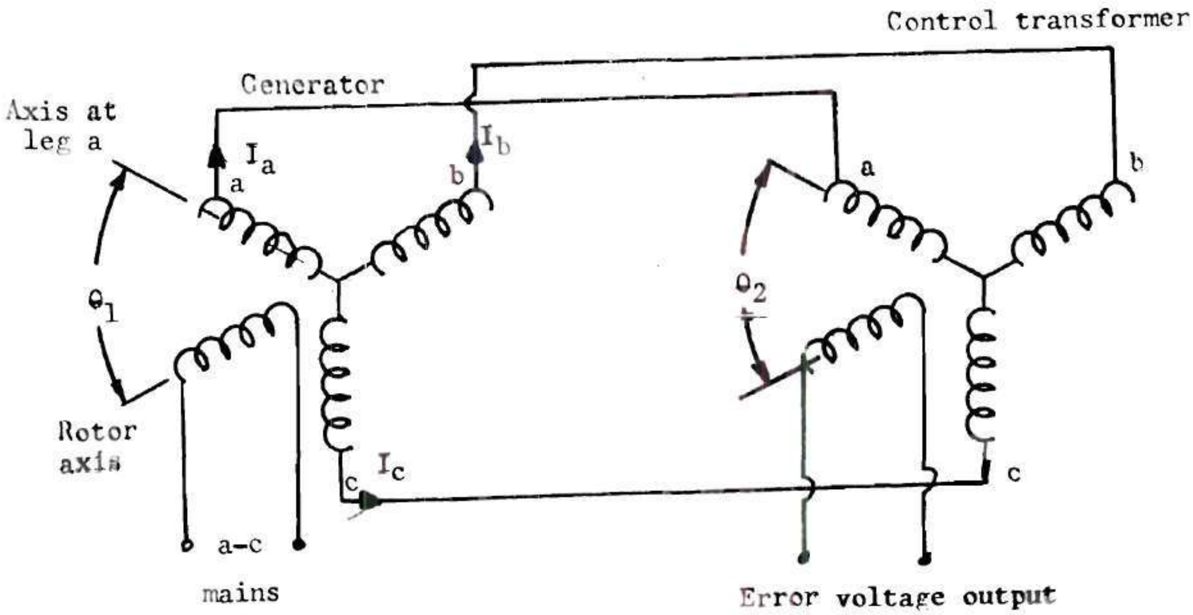

Fig. 41, Synchro Generator-Transformer System for Evaluation of Error Voltage.

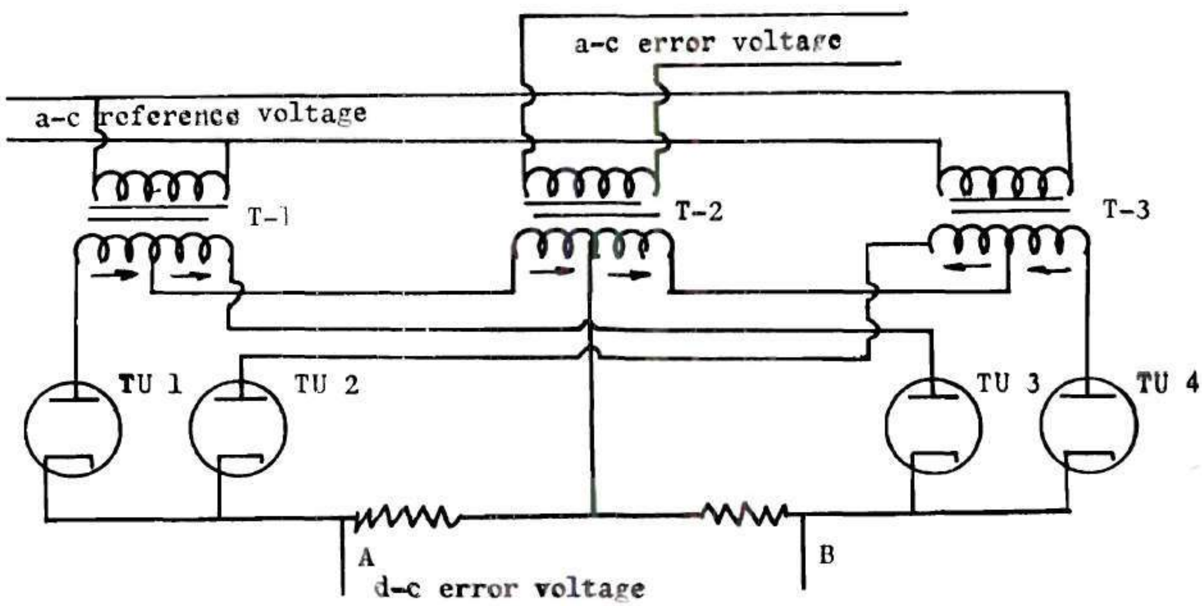

Fig. 42. Discriminator Circuit.

voltage induced in one leg of the generator stator winding when the axis of that leg coincides with the rotor-winding axis. Assume that the induced voltage varies as the cosine of the angle between the leg and rotor winding axes. If θ_1 is the angle between the leg-a and rotor winding axes, the voltages in the three legs are

$$E_a = E_1 \cos \theta_1$$

$$E_b = E_1 \cos (\theta_1 - 120^\circ)$$

$$E_c = E_1 \cos (\theta_1 - 240^\circ)$$

Let L be the total self inductance of one leg of the generator stator, one leg of the transformer stator, and the interconnecting line. Let M be the sum of the mutual inductance between generator-stator legs plus that between transformer stator legs. Equations involving the three leg currents I_a, I_b, and I_c may be written by noting that the voltage between stator junctions is the same regardless of the path followed. Accordingly,

$$E_1 \cos \theta_1 - jwLI_a - jwM(I_b + I_c)$$

$$= E_1 \cos (\theta_1 - 120^\circ) - jwLI_b - jwM\,(I_a + I_c)$$

$$= E_1 \cos (\theta_1 - 240^\circ) - jwLI_c - jwM\,(I_a + I_b)$$

$$I_a + I_b + I_c = 0$$

Simultaneous solution of these equations yields

$$jwI_a = \frac{E_1}{L-M} \cos \theta_1$$

$$jwI_b = \frac{E_1}{L-M} \cos(\theta - 120^\circ)$$

and

$$jwI_c = \frac{E_1}{L-M} \cos(\theta - 240^\circ)$$

The mutual inductance between a transformer stator leg and the transformer rotor winding has the maximum value M_t and varies as the cosine of the angle between that leg and the rotor axis. When θ_2 is the angle between leg a and the rotor winding, the error voltage induced in the rotor is

$$E_e = jwI_aM_t \cos\theta_2 + jwI_bM_t \cos(\theta_2 - 120^\circ)$$
$$+ jwI_cM_t \cos(\theta_2 - 240^\circ)$$

Upon substitution of the three preceding formulas into this one, the error voltage becomes

$$E_e = \frac{3}{2} E_1 \frac{M_t}{L-M} \cos(\theta_2 - \theta_1)$$

This result reveals that the error voltage is zero when the shaft displacement is 90 degrees; it also shows that the magnitude of the error voltage varies sinusoidally with the departure from this equilibrium displacement. (3)

The discriminator.--The error signal from the control transformer is an alternating voltage which undergoes a phase reversal when the rotor passes through the zero point. It is desired, in the proposed servomechanism that this alternating voltage be converted into a reversible polarity d-c voltage.

The discriminator is a phase sensitive rectifier. In Fig. 42 the circuit of a discriminator is shown. The a-c error voltage is connected to transformer T-2, while the a-c reference voltage is connected to transformers T-1 and T-3. This voltage should be in phase with or 180 degrees out of phase with the a-c error voltage; therefore, this voltage should be connected to the same source as that of the synchro generator. The output d-c voltage is taken across terminals A and B.

If the error voltage is zero, the magnitude of the applied voltage to each of the four rectifier tubes is equal. Tubes one and four conduct during one half of the cycle, and tubes two and three conduct during the other half of the cycle. The resistances R_1 and R_2 are equal in magnitude, and, since equal currents pass through them, the voltage across each will be equal. The total voltage then across R_1 and R_2 or from terminals A and B will be zero.

Assume the magnitude of the error voltage equals that of the reference voltage. Tubes one and two will conduct as a full wave rectifier, or, if the phase of the error voltage is reversed, tubes three and four will conduct. A d-c voltage will appear across R_1 and R_2 as determined by the phase of the error voltage. Therefore, it can be seen that a reversible polarity d-c voltage will appear across terminals AB. The polarity will be determined by the phase of the error voltage.

The magnitude of the d-c output voltage will be in proportion to the magnitude of the a-c error voltage, and the polarity of the d-c voltage will depend upon the phase polarity of the a-c error voltage.

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